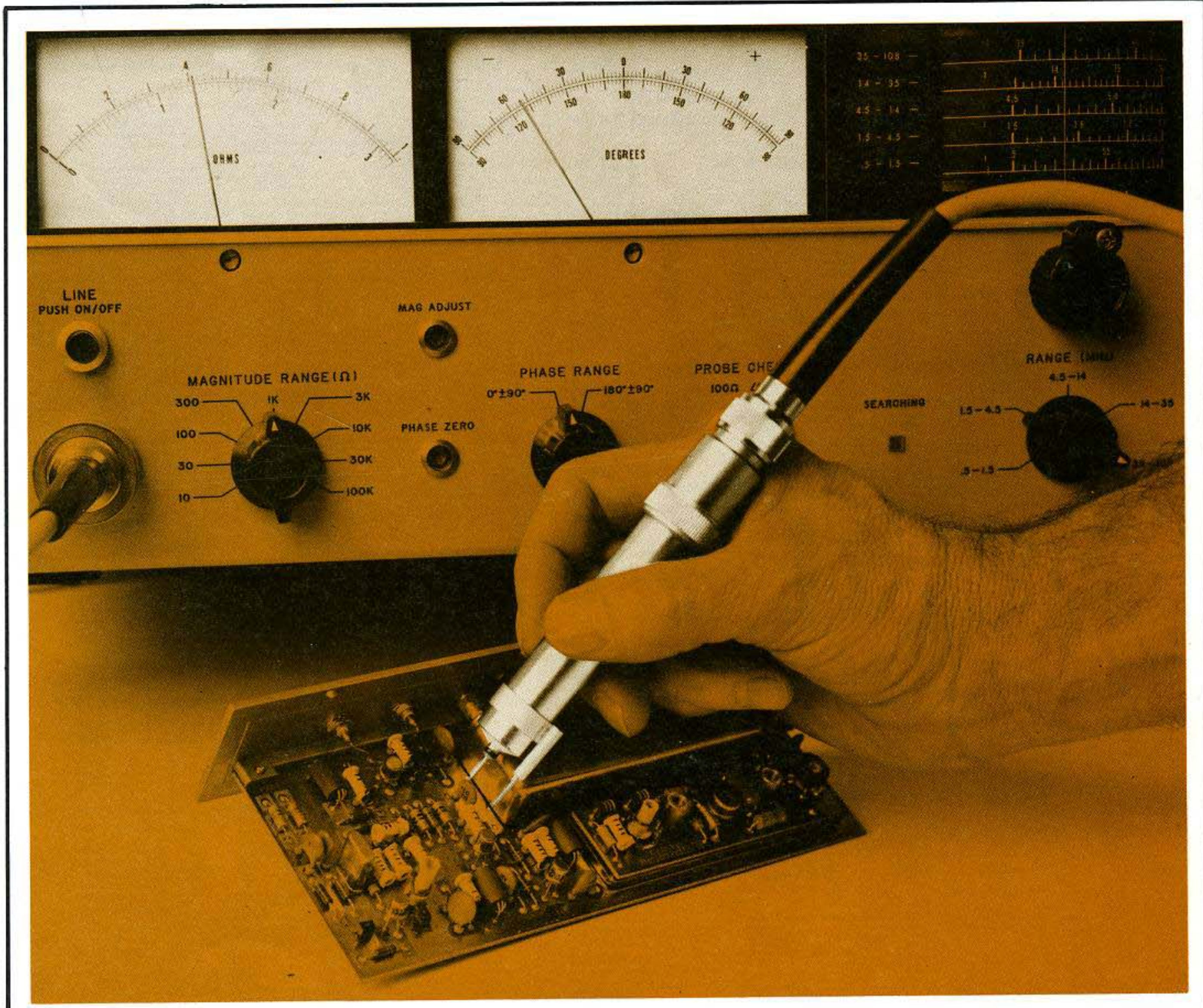
APPLICATION NOTE 86

Using the Vector Impedance Meters



HEWLETT PACKARD

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SECTION I
INTRODUCTION

Like voltage and current, impedance is an important quantity to the design engineer. Unlike the other two parameters, however, impedance is more tedious for the engineer to measure. The basic difficulty with impedance measurement has been the lack of suitable broadband, general purpose instrumentation for the task. As a result, the design engineer is reduced to verifying his predicted results by using bridge techniques. Thus, the evaluation of wide ranges of impedance over wide frequency ranges has been a long, tedious process involving point-by-data collection and interpretation.

In recognition of the design engineer's requirement for a general purpose impedance measuring device, Hewlett-Packard engineers developed the 4800A and 4815A Vector Impedance Meters to cover the frequency range between 5 Hz and 108 MHz. These instruments are general purpose in the same sense as the broadband oscilloscope, the ac vacuum tube voltmeter, and the frequency counter. That is to say, they allow the user the flexibility of rapidly making measurements over wide frequency and impedance ranges directly in the parameter of interest to him. In essence, the instruments provide the design engineer with a fundamentally new class of instrumentation.

If one recalls the fundamental relationship in the series equivalent circuit, driving-point impedance is defined as the ratio of the voltage applied to the current entering one port of the circuit. It may be represented vectorially either as a point in the complex impedance plane having Cartesian coordinates $R \pm jX$ or polar coordinates $|Z| \underline{/\theta}$, where θ is the angle between the voltage and current vectors.

Operation of the Vector Impedance Meters is based directly on this fundamental definition of driving-point impedance, and the impedance vector is read out in the polar coordinates $Z \underline{/\theta}$. Figure 1 is a simplified block diagram of the typical Vector Impedance Meter. In operation, a broadband oscillator applies a CW signal to an amplifier with leveled output. Current from the amplifier then passes through the unknown component, mounted across terminals A and B, that is to be measured. Current passes from the B terminal through the ammeter to ground. Thus, the current through the unknown is sensed by the ammeter and used to generate a leveled signal that, in turn, levels the output of the amplifier. The leveling then holds the current through the unknown constant. Since $Z = E/I$ and I is now a constant, Z is directly proportional to the voltage across the unknown. Therefore, a high impedance, broadband voltmeter is placed across terminals A and B, and the output is calibrated directly in impedance.

The magnitude of the driving-point impedance vector has been established, and it is only necessary to determine the phase angle existing between the voltage across and the current through the unknown. To measure phase angle, ac outputs from both the voltmeter and ammeter are used to trigger a zero-crossing phase detector which is calibrated directly in phase angle.

Thus, the Vector Impedance Meters represent a complete measuring system consisting of an excitation oscillator, broadband voltmeter, ammeter, and phase meter. The entire system is calibrated in the parameter of interest, impedance, and the inaccuracies of all elements in the system are taken into

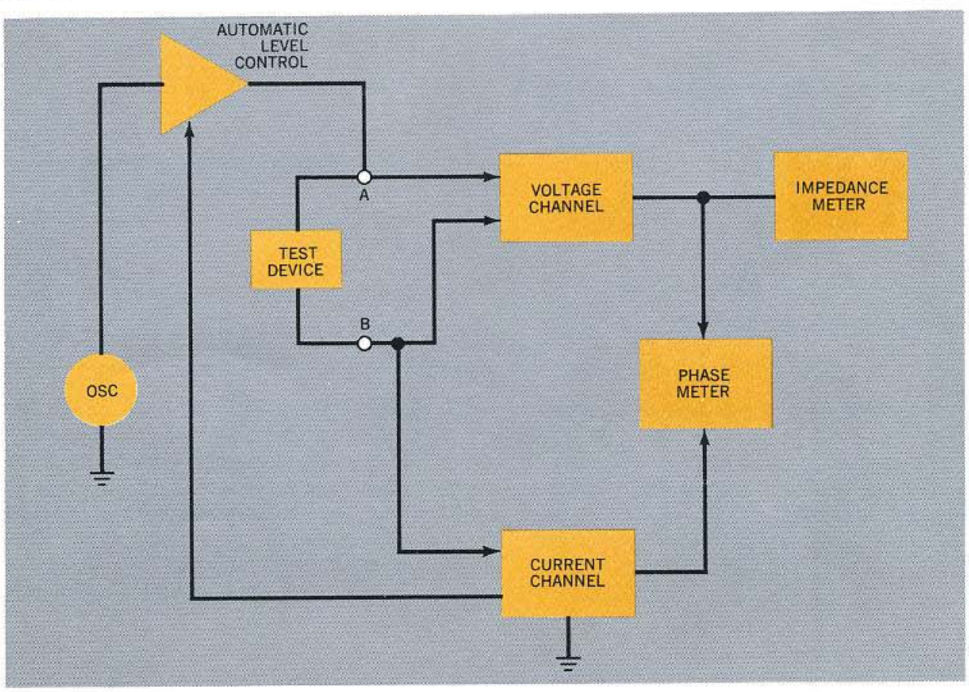
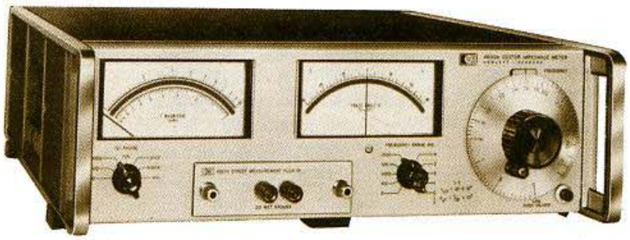


Fig. 1. Simplified Block Diagram — Vector Impedance Meters.

account so that the driving-point impedance may be measured with known accuracy.

Two Vector Impedance Meters are available, both operating with the same basic concept. The 4800A Vector Impedance Meter covers the frequency range from 5 Hz to 500 kHz. It utilizes two measuring terminals. Both terminals are above ground and



The HP Model 4800A Vector Impedance Meter covers the 5 Hz to 500 kHz frequency range. Measurements are made at two ungrounded banana plug terminals.

The HP Model 4815A RF Vector Impedance Meter covers the 500 kHz to 108 MHz frequency range. Measuring terminals are contained in a probe which may be used to make in-circuit measurements referenced to ground.

Fig. 2. Vector Impedance Meters.

are connected directly to the amplifier circuits. The 4815A RF Vector Impedance Meter operates from 500 kHz to 108 MHz and uses the synchronous sampling technique to convert the RF signal to be measured to a narrow-band IF of 5 kHz. It measures impedance at the tip of a probe with respect to ground. Both instruments measure the unnormalized impedance, therefore, they are not referenced to any characteristic system impedance. The instruments are completely specified as vector impedance systems containing everything necessary to make direct, instantaneous driving-point impedance measurements.

Measurements of passive circuits and devices are the most common measurements made with the Vector Impedance Meters. These measurements are made by simply connecting the "unknown" to the instrument and setting the frequency as desired. The vector impedance readout gives the driving-point impedance of the "unknown" over the frequency range of interest. Perhaps the greatest single application of the Vector Impedance Meters is that of evaluating the actual impedance of real circuit elements such as resistors, inductors, and capacitors. The circuit elements are never ideal, and calculating the exact impedance is difficult. The Vector Impedance Meters not only give a fast measure of the actual impedances, but also, allow the engineer to evaluate the parasitics associated with real elements.

Other areas of application include measurements with dc biasing. Diodes, varactors, and electrolytic capacitors are some of the devices discussed in this category. The Vector Impedance Meters can even be used in some measurements where noise and other ac signals are present. Examples are transducers, mixers, and antennas.

This Application Note describes a number of useful measurements that can be made with these devices and details some of the precautions to be taken and "techniques" that must be used.

SECTION II
EVALUATING COMPONENTS

The Vector Impedance Meters offer an extremely versatile technique for measuring the resistance, inductance, and capacitance of circuit components. These devices may be connected directly to the measuring terminals and their complex impedance examined rapidly at specific frequencies of interest over a range of frequencies. The presence of phase information in this measurement is quite valuable since it provides a good indicator of the extent to which the real element approaches the ideal counterpart. At certain specific frequencies, the value of series reactive elements may be measured with the readout directly in their primary units (microhenries or microfarads). When measuring components, the following relationship should be kept in mind for series equivalent circuits.

$$R = |Z| \cos\theta$$

$$L = \frac{|Z|\ |\sin\theta|}{2\pi f} \text{ for } 0^\circ < \theta < 180^\circ$$

$$C = \frac{1}{|\sin\theta|\ |Z|\ 2\pi f} \text{ for } -180^\circ < \theta < 0^\circ$$

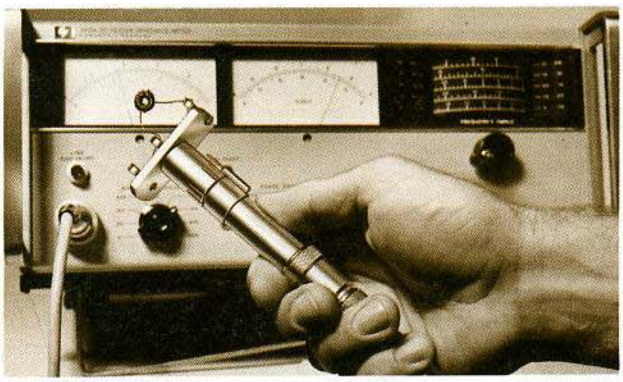


Fig. 3. Discrete components may be measured at high frequencies with the 4815A by clipping them to the component mounting adapter.

DIRECT MEASUREMENTS

The resistor measurement is, of course, the most straightforward. Since frequency does not enter directly into the formula, any frequency where the phase angle is within $\pm 5^\circ$ of 0° will yield the resistance at that frequency. It is possible to find some frequencies where certain types of resistors will show a significant inductive or even capacitive reactance. This is generally a result of lead inductance or inter-winding capacitance.

Figure 4 shows the type data that may be obtained from measurements of resistors. The frequency dependency of three 200-ohm, 1% precision resistors of different constructions was measured. Curve 1 presents the data for a metal film resistor. It can be seen, that although the component is slightly capacitive (small negative phase angle), its value is relatively constant over the range of interest. Curve 2 presents data for an inductively compensated wire-

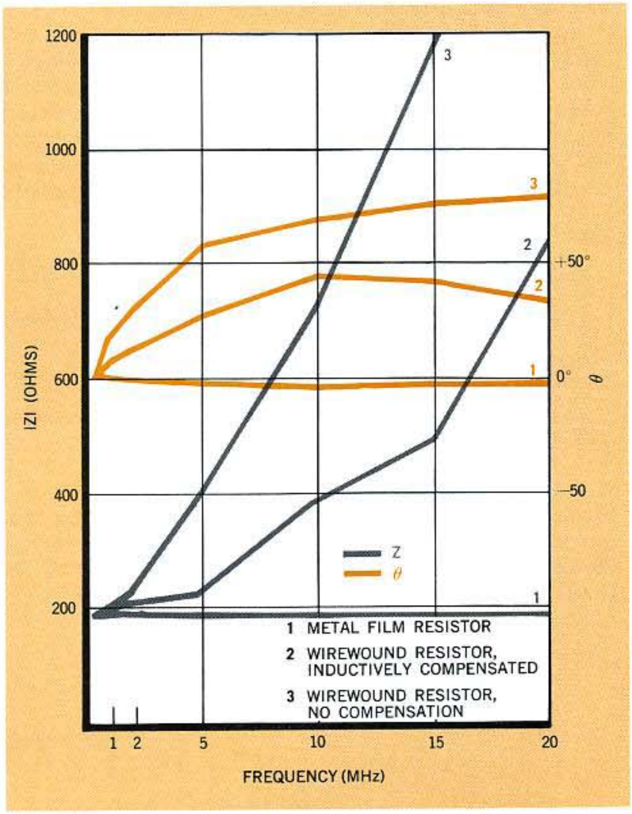


Fig. 4. Typical data obtainable from measuring resistors with the Vector Impedance Meters.

wound resistor. Note that its usefulness degenerates rapidly above 5 MHz due to the uncompensated inductance. Curve 3 shows an uncompensated wirewound resistor. It can be seen that it is practically useless above 1 MHz. In this illustration, the black curves show the absolute magnitude of impedance; the color curves show the value of the phase angle.

Reactive elements can be quickly characterized in terms of Z, θ over the operating frequency range with the Vector Impedance Meters. In addition, both inductors and capacitors can be measured in their primary units (μH or μF) by selecting a frequency where the phase angle is within 5° of $\pm 90^\circ$ respectively. Also, the frequency should be related to $1/2\pi$ or approximately 0.159 by a power of ten.

$$f = \frac{1}{2\pi} \times 10^n$$

For ease of operation, the 4800A frequency dial has "LC" inscribed at 15.9 and the 4815A has an arrow head at 1.59 MHz and 15.9 MHz. Thus, at the frequencies of 15.9 Hz, 159 Hz, 1.59 kHz, 159 kHz, 1.59 MHz, and 15.9 MHz, the impedance scales are calibrated directly in microhenries or microfarads and components may be measured directly.

For instance, the 4800A frequency dial may be set to 1.59 kHz and the instrument used as a bridge would normally be used. However, in this application the 4800A will read an unknown component, together with all of its associated distributed parameters, quickly and directly without the nulling and balancing operation required for bridge operation. The following table gives the scale factors that apply when the 4800A is operated in this mode.

Z Range	Direct Reading C Range	Direct Reading L Range
X1	10 μF - 100 μF	100 μH - 1 mH
X10	1 μF - 10 μF	1 mH - 10 mH
X100	.1 μF - 1 μF	10 mH - 100 mH
X1K	.01 μF - .1 μF	100 mH - 1 H
X10K	1000 pF - .01 μF	1 H - 10 H
X100K	100 pF - 1000 pF	10 H - 100 H
X1M	10 pF - 100 pF	

Table 1. Direct reading values when the 4800A is operated at 1.59 kHz.

The following measurements were made on a toroidal inductor with a ferrite core. As the frequency is varied, the inductor appears resistive, then inductive, then resistive at self-resonance, and finally capacitive.

Frequency	|Z|	/Θ
159 Hz	1.10Ω	0^o
15.9 MHz	1.91KΩ	90^o
29.3 MHz	96.0KΩ	0^o
43.5 MHz	3.10KΩ	-88^o

$L = |Z| \times 10^n$ in μH
at 15.9 MHz: n = -2, L = 19.1 μH

A capacitor can be evaluated in a similar manner. As the frequency is increased it appears capacitive, resistive at resonance, and then inductive. The data below was obtained from a 1500 pF dipped mica capacitor. Note that the capacitor is self-resonant at 25.7 MHz.

Frequency	|Z|	/Θ
1.59 MHz	67Ω	-88^o
25.7 MHz	0.6Ω	0^o
60.0 MHz	7.9Ω	84^o

$C = \frac{1}{|Z|} \times 10^n$ in μF
at 1.59: n = -1, C = 1500 pF

SORTING COMPONENTS

The straightforward operation of the 4800A Vector Impedance Meter and high repeatability between measurements make the instrument valuable for go-no-go checkout. For example, resistors, capacitors, and inductors can be sorted to assure that they fall within limits of some standard. To take advantage of the high repeatability (on the order of 1 part in 10^3 under normal laboratory conditions) a digital voltmeter such as the -hp- 3440A may be connected to the magnitude analog output. An -hp- 5050A Recorder can be tied in for recording purposes. Measurements can be made at approximately one reading every 5 seconds.

Table 2 shows the deviation of a group of inductors with respect to a standard. The impedance magnitude of the standard at 120 kHz is 2.80 ohms and has an inductance of 3.90 μH. Six of the inductors checked on the 4800A Vector Impedance Meter fall within 1% of the standard; i. e., 2.78 to 2.83 ohms. Another six inductors are less than the 2.80 ohms standard by at least 1%; and the last group of six is greater than the standard by at least 1%.

No Go >-1%	Go within 1% of standard			No Go >+1%
		Standard		
2.67	2.78	2.80	2.81	2.84
2.73	2.78		2.82	2.84
2.73	2.79		2.83	2.85
2.75				2.87
2.77				2.88
2.77				3.03

L = 3.90 μH, f = 120 kHz, |Z| in ohms

Table 2. Go — no-go inductor check.

Capacitors can also be sorted using the 4800A Vector Impedance Meter. As with inductors, the capacitors can be chosen to have a specified capacitance or a specified impedance at a given frequency. Tolerances can be set as desired keeping in mind both the repeatability and accuracy (±5%). The following measurements were taken on a 1 pF ±0.5 pF dipped mica capacitor at 159.2 kHz:

	C (pF)	Z (MΩ)	
C_1	0.817	1.23	
C_2	0.847	1.19	
C_3	0.849	1.18	
C_4	0.853	1.17	
C_5	0.859	1.16	
C_6	0.992	1.01	±5%
C_7	1.00	1.00	±5%
C_8	1.03	0.98	±5%

C6 and C8 fall within ±5% of C7. C7 is 1.00 pF to an accuracy of ±7%. By using the Vector Impedance Meter, capacitors which vary by as much as ±50% in this case can be quickly sorted to fall within ±5% of a given value. Since the measuring terminals of the 4800A are balanced with respect to ground, extremely small capacitors can be measured directly.

Similar measurements may be made with the 4815A; although, in general, the achievable repeatability is not as high as that with the 4800A.

CHARACTERIZING TERMINALS OR FIXTURES

Either the 4800A or the 4815A has the capability to characterize the residual impedances associated with its own terminals. Fixtures attached to the measuring terminals may be also characterized; and, if desired, their equivalent circuit developed. This allows measured data to be quickly and accurately corrected if necessary. For instance, the measuring terminal residual impedance of a typical 4800A may be quickly determined by setting its frequency to 159 kHz and adjusting the impedance range switch for an on-scale reading. In making this measurement on a standard production line instrument, an impedance reading of 6 megohms, phase angle -90^o was obtained, indicating that the terminal residual placed in parallel with the unknown component is .16 picofarads. If a fixture is to be placed on these terminals it may be also characterized. In this particular case, it was desired to provide component mounting using quick connect spring clips for the component mounting adapter. The adapter was placed on the terminals and the new residual terminal impedance was measured. The value with the component mounting adapter attached to the terminals was 1.25 megohms, phase angle -90^o indicating that the terminal capacitance had been increased to .8 picofarads.

CHARACTERIZING CRYSTALS

Another component which is quickly and thoroughly analyzed with the Vector Impedance Meters is the quartz crystal. Each resonant mode of a crystal may be represented by the equivalent circuit in Figure 5.

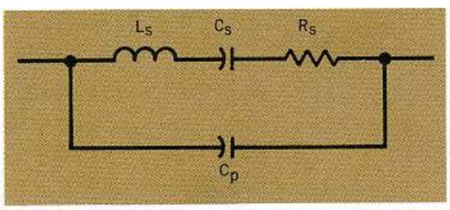


Fig. 5. Equivalent circuit of a crystal resonance.

This circuit exhibits a series and parallel resonance very close in frequency to the series resonance which occurs at the lower of the two frequencies. R_s is observed directly by tuning to series resonance and reading the impedance magnitude. Since the series resonant impedance is generally very small, the 0.5-ohm probe residual should be subtracted when using the 4815A. If a counter such as the -hp- 5245L, is connected to the RF output, the frequencies of series and parallel resonance may be determined. One additional measurement will permit all of the elements of the equivalent circuit to be computed.

If the Vector Impedance Meter is tuned to a frequency slightly below series resonance, the impedance measured is the reactance of C_p and C_s in parallel. In other words, the total parallel capacitance, C_T, can be measured. All of the values may now be computed from the following formulae.

$$C_p = C_T \frac{f_s}{f_p} \text{ or } C_p \approx C_T, \text{ since } f_s \approx f_p$$

$$C_s \approx C_T \frac{2(f_p - f_s)}{f_p}, \text{ since } f_s \approx f_p$$

$$L = \frac{1}{4\pi^2 f_s^2 C_s}$$

where f_s is the series resonance frequency and f_p is the parallel resonance frequency.

The Q of a crystal resonance is determined by the bandwidth method. An external oscillator input permits a frequency synthesizer, such as the -hp-5100A/5110A, to be used as a high-accuracy, high-resolution signal source, if desired.

A typical crystal has a fundamental resonance and a number of harmonically related resonances. It may also have a number of spurious resonance modes. Each of these takes the form of the equivalent circuit, such as described above.

For many fundamental crystal resonances, the impedance at parallel resonance will be greater than full scale of the Vector Impedance Meter. The reading is brought on scale by placing a 100K-ohm resistor in parallel with the crystal. The approximate impedance of the crystal can then be estimated. A metal film resistor is recommended for this purpose. Measure it separately and use this reading.

The following example shows typical crystal measurements. Results of these measurements are shown graphically in Figure 6.

$$f_s = 27.6658 \text{ MHz}, \ Z_s = 18.4\Omega \angle 0^o$$
$$f_p = 27.6701 \text{ MHz}, \ Z_p = 23.5K\Omega \angle 0^o$$

f_s and f_p are measured with an HP 5245L Counter.

The 0.5-ohm probe residual should be subtracted from Z_s.

$$R_s = 18.4 - 0.5 = 17.9\Omega$$
$$R_p = 23.5K\Omega$$

C_T is found by setting the impedance meter to a frequency, just below series resonance, where the phase is approximately -90^o. The impedance at this point is 182Ω, $\angle -82^o$.

$$C_T = \frac{1}{\omega Z} = \frac{1}{(2\pi)(27 \times 10^6)(182)} = 35 \text{ pF}$$

Any desired correction for stray capacitance should be subtracted from C_T.

Using the above formulae:

$$C_p \approx C_T = 35 \text{ pF}$$

$$C_s \approx C_T \frac{2(f_p - f_s)}{f_p} = 10.5 \text{ fF}$$

$$L = \frac{1}{4\pi^2 f_s^2 C_s} = 5.4 \text{ mH}$$

The Q of the crystal at series resonance is found by measuring the center frequency at series resonand the frequencies at both ±45°.

$$Q = \frac{f_s}{\Delta f} = \frac{27.66584}{27.66596 - 27.66572} = 1.15 \times 10^5$$

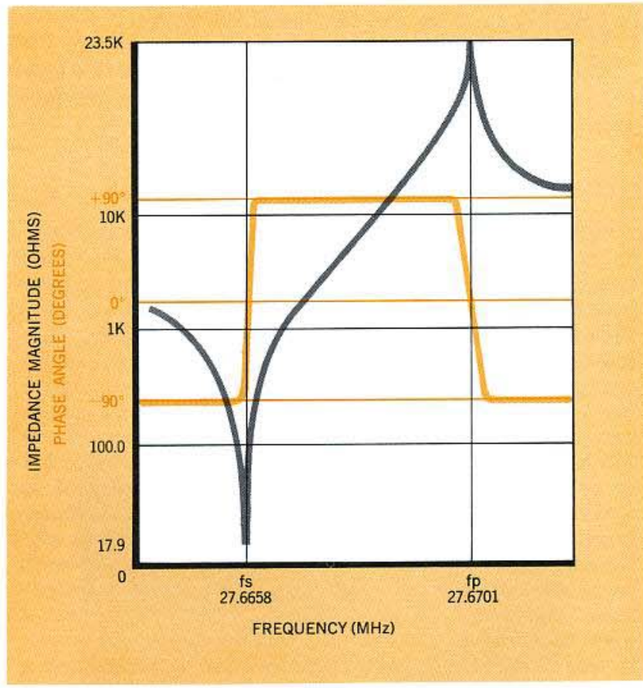


Fig. 6. Impedance magnitude and phase as a function of frequency in the region of series and parallel crystal resonance.

SECTION III
TRANSMISSION LINE MEASUREMENTS

The Vector Impedance Meters may be used to measure characteristic impedance, attenuation, length, and velocity of propagation of transmission lines. The speed with which the measurements can be accomplished on relatively short pieces of cable and the accuracy realized in using the simple, direct techniques described below, has made the instrument a valuable tool for the design engineer concerned with coaxial elements, as well as for the quality control engineer making spot checks during the manufacture of cable. These techniques are of primary interest at RF frequencies so that use of the RF Vector Impedance Meter is implied. Figure 7 shows the 4815A measuring coaxial cable parameters.

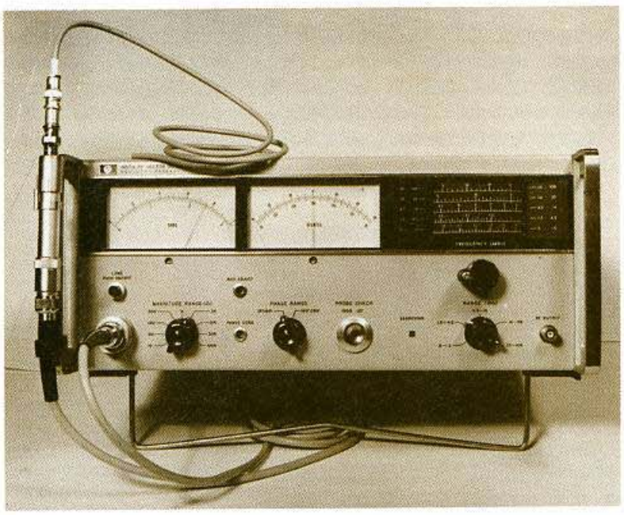


Fig. 7. The 4815A RF Vector Impedance Meter may be used to measure transmission line parameters. Z_o a, and C are readily determined.

CHARACTERISTIC IMPEDANCE

Several methods are available for the measurement of characteristic impedance (Z_o) with the RF Vector Impedance Meter. One of the most satisfactory involves the familiar relationship, $Z_o = \sqrt{Z_i \ Z_L}$, where Z_i is the input impedance of a quarter-wavelength line with a given termination, and Z_L is the impedance of the termination itself. For simplicity, this relation is used in the form $Z_o = \sqrt{R_1 R_2}$, where R_1 is a resistance measured directly on the RF Vector Impedance Meter terminals and R_2 is the input resistance of the quarter-wave line terminated by R_1. The actual procedure used for this measurement is given below.

The RF Vector Impedance Meter is set to the desired measuring frequency. A piece of the sample cable is cut to a length corresponding to approximately one quarter-wavelength with both ends cut back just enough to expose the center conductor and shield. If the cable dielectric is solid coaxial polyethylene, this length may be taken directly from Figure 8.

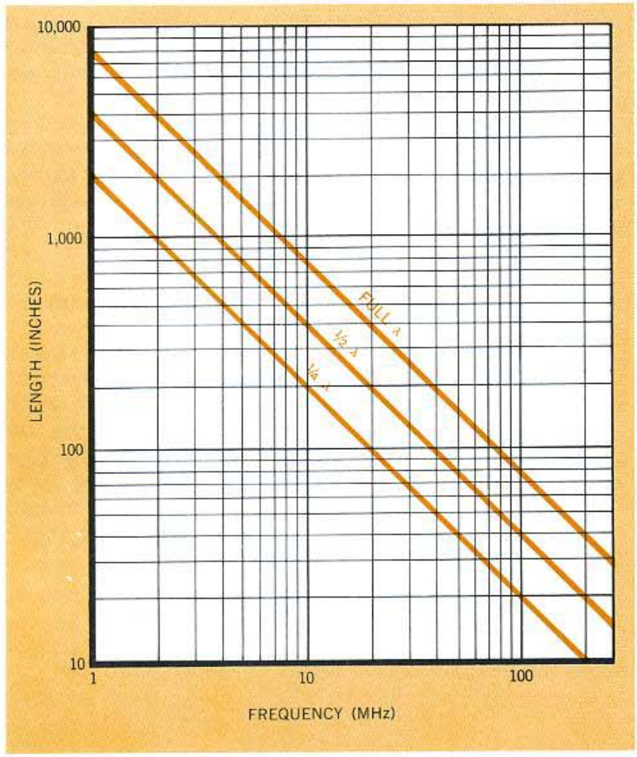


Fig. 8. Wavelength vs. frequency for coaxial cables having polyethylene dialectric.

To verify the correct cable length, one end should be shorted and the other connected to the 4815A. The 4815A should show a phase of zero degrees if the cable is exactly $\lambda/4$. If it reads negative, the frequency should be lowered or the cable shortened. Likewise, a positive phase angle indicates too high a frequency or too short a cable. Since the characteristic impedance does not change significantly for polyethylene at frequencies above 20 MHz, it is usually more convenient to adjust the frequency.

For the termination, select a resistor whose resistance is roughly equal to the estimated characteristic impedance of the cable. If the latter cannot be estimated, 50 ohms will usually suffice. Remove the short circuit from the end of the quarter-wavelength line and connect the resistor in its place, keeping the leads as short as possible. Now record the Z meter reading as R_1. The resistor should then be removed from the end of the cable and measured directly across the probe to provide the value R_2.

In a typical measurement, made on a quarter-wavelength section of RG 58/U cable, a resistor which measured 47 ohms directly across the probe, was used to terminate the line. The line with this termination measured 64 ohms. Then,

$$Z_o = \sqrt{64 \times 47} = 55\Omega$$

Since the line is a quarter-wavelength section, the phase angle should be approximately zero.

An equally satisfactory method of determining Z_o is based on the relationship:

$$Z_o = \frac{101,600}{v \times C}$$

where v is the velocity of propogation factor in percent and C is the cable capacitance in pF per foot.

The latter value is determined by attaching a very short length of the cable; i.e., less than $\lambda/4$, to the RF Vector Impedance Meter and measuring C_p directly. The velocity of propagation may be determined as described in a later section.

A third method of measuring Z_o may be worth mentioning, although it is less satisfactory with respect to accuracy.

This method is implied by equation (3) on Page 29 in the Appendix, which indicates that the characteristic impedance of a lossless line is equal to the absolute value of the reactance of a short-circuit section 1/8 wavelength long.

To obtain the correct length, a quarter-wave section is first established in the manner described above, at a frequency twice the desired measuring frequency. This frequency is then halved and the reactance of the short-circuited section determined from the phase reading of $\pm 45^o$.

ATTENUATION

A convenient method of measuring attenuation, using short pieces of cable, is provided by the equation,

$$\alpha L = \frac{Z_o \times 8.69 \text{ dB}}{Z_i}$$

where α is dB per unit length, L is length, and 8.69 is the constant of proportionality. Here the value of Z_i is determined by measuring the parallel resistance of a piece of cable half-wavelength long open circuited at the far end. If the frequency is such that a half wavelength is less than approximately 4 feet, a one or three-halves wavelength piece can be used, with no change in procedure, to minimize the effect of irregularities in the cable. The attenuation in dB obtained for the length of cable tested can be readily adjusted to dB per 100 feet.

When the desired frequency has been selected, cut the cable to one-half wavelength, and cut one end back only enough to make contact. Connect the cable with the far end open circuited to the RF Vector Impedance Meter. The meter should indicate a phase angle of approximately zero. If the phase is negative, either lower the frequency or shorten the cable slightly. On the other hand, a positive phase requires a slightly longer cable or higher frequency. With the phase equal to zero, the |Z| meter reading is the proper value for Z_i to be used in the equation. As an example, a one-half wavelength section of RG-58/U cable at 77MHz (52" long) was found to have a Z_i of 2750 ohms. Applying this value to the formula above, together with the known characteristic impedance of 55 ohms, and adjusting for the length of the section, the attenuation was found to be 3.98 dB per 100 feet.

BALANCED TRANSMISSION LINE CHARACTERISTICS

Dual or balanced transmission lines, such as "twin lead", cannot be measured by direct connection to the RF Vector Impedance Meter, but must be attached through a "balun". The function of the balun is to supply an RF signal which is equal and opposite in phase to each conductor of the balanced line, while providing an equally high resistance path to ground for both elements. There are a number of forms which can be used, depending on the situation. Several commercial types are available if desired. Probably the simplest type of balun can be made by doubling a one-half wavelength section of coaxial line and connecting the outer conductors at the ends. The outer conductors are then connected to the probe ground and one center conductor is connected to the center pin. The balanced line may then be connected to both center conductors. Figure 9 illustrates such a balun connected at the end of a half wavelength resonant section. Since this type of balun acts as a 2:1 voltage transformer, or a 4:1 impedance transformer, the factor 4 must be used in computing the desired characteristic from the measurements made.

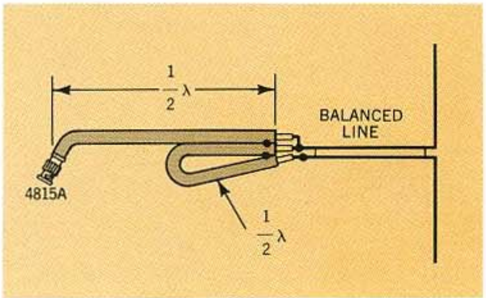


Fig. 9. Diagram of half-wavelength balun.

To make transmission line measurements with this type balun, the following procedure is used.

Characteristic Impedance

1. Measure the balun, open-circuited, on the RF Vector Impedance Meter. If the length is correct, the phase should equal approximately 0^o. If not, readjust the frequency slightly until the length is correct.

2. Measure and cut a section of the balanced line to be measured slightly longer than one-quarter wavelength and attach it to the balun with the far end shorted. Shorten the line gradually by cutting off small pieces, until the phase once again is essentially 0^o. (Do not readjust frequency.)

3. Connect a resistor, which is close to the estimated line impedance and nonreactive, to the far end of the quarter-wave line and measure the impedance of the combination. Record this value as Z_1.

4. Measure the Z of the resistor connected directly to the probe. Call this value R_2.

5. Then, the characteristic impedance of the quarter-wave cable is given by:

$$Z_o = \sqrt{Z_1 Z_2}$$

Attenuation

1. Measure the balun open circuited, making sure that the phase is approximately equal to zero. Record Z as R_1.

2. Measure a half-wavelength section (or multiple thereof, to provide a minimum length of 4 feet), open circuited at the far end, and record the result, $|Z|$ as R_2.

3. Then the parallel resistance of the cable (R_3), as seen through the balun, is:

$$R_3 = 4 \frac{(R_1 R_2)}{(R_1 - R_2)}$$

4. Attenuation is:

$$\frac{dB}{100 \text{ ft.}} \approx \frac{Z_o}{R_3} \times 8.69 \times \frac{1200}{\text{length of cable in inches}}$$

Electrical Length

The measurement of electrical length of cables is based on quarter-wavelength resonances. Providing the cable is not too long, the cable will resonate at each quarter-wavelength multiple. Therefore, the frequency difference between any two adjacent resonances will be the frequency corresponding to one-quarter wavelength.

To make electrical length measurements, one end of the cable should be shorted. This will assure a large standing wave to detect a resonance. Next, the impedance meter should be adjusted until a resonance frequency is found. The impedance magnitude range should be switched to maintain an on-scale reading. Finally, the frequency should be adjusted upward or downward until the next resonance is found. The frequency difference between these two adjacent resonances will be the frequency of a quarter-wavelength cable. Check to be sure that these two frequencies are adjacent. One will show a large impedance, the other a small impedance. This necessarily follows since one is an even quarter-wavelength multiple and the other an odd multiple. All odd quarter-wavelength resonances will have a high impedance if the cable is shorted.

The following example will clarify the technique. First, the cable is shorted. The lowest frequency of resonance is 50.7 MHz and has an impedance of 3.62 KΩ 0°. Tuning upward in frequency, the next resonance is found at 99.9 MHz and shows an impedance of 1.40Ω $\angle 0°$. The difference between the two resonant frequencies is 49.2 MHz. It follows that the frequency differences between these resonances is the frequency of a quarter-wavelength section. The electrical length, l_e, can now be calculated from the formula:

$$l_e = \frac{c}{4\Delta F}$$

where c is 3×10^8 m/sec and ΔF is the frequency difference between adjacent quarter-wavelength resonances. For the example used $l_e = 1.5$ m.

The actual physical length l_p of the cable may be determined from the relationship $l_p = l_e/\sqrt{\epsilon}$ providing the dielectric constant of the cable is known. Measurements of length with the 4815A are, however, limited to cable lengths of about 150 meters of air line. Also, as a matter of technique, the first quarter-wave resonance should be found at the lowest frequency within the range of the instrument. This technique also allows cables to be cut to a known electrical length or two cables to be cut to the same electrical length.

BALANCED MEASUREMENTS USING A BROADBAND BALUN

A broadband balun makes possible balanced measurements with the 4815A. The balun in effect puts a large reactance between the unknown and the probe ground. It also acts as a transmission line. In other words, the unknown appears as the termination of a transmission line with length equivalent to that of the balun. Thus, to find the impedance of the unknown, the impedance transformation must be determined.

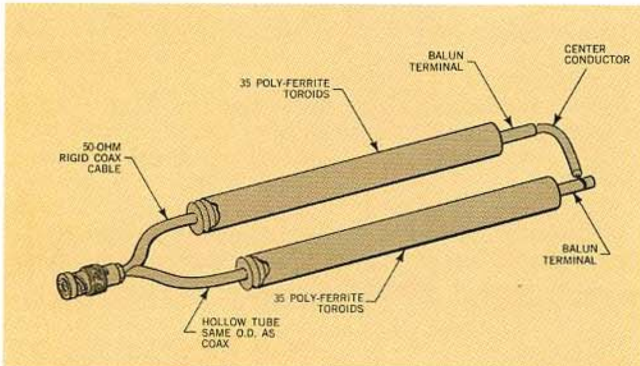


Fig. 10. Construction of a broadband balun.

The diagram, Figure 10, shows the construction of a broadband balun. It consists of a rigid coaxial cable approximately 7 inches long and another conductor of the same diameter. Ferrite toroids are placed around both conductors to create a high impedance to ground. The inner conductor of the coax is connected to the other conductor and the two rigid cables are joined at one end as shown. A BNC connector is used to connect to the 4815A probe.

The toroids around the outer conductor of the coax produce a high impedance between the balanced terminal output and ground. As a result, both the inner conductor and outer conductor are above ground. Thus, the two terminals see the same impedance to ground and are effectively balanced.

The impedance correction for the electrical length of the balun is quickly accomplished with the help of a $Z \angle \Theta$ chart. (The $Z \angle \Theta$ Chart is a Smith Chart expressed in terms of Z and Θ, rather than R and X.) By measuring the impedance of the balun terminated in a short and locating this point on the $Z \angle\Theta$ chart, the wavelength at one frequency is determined. All measurements with an unknown terminal should be rotated the wavelength of the balun to account for the impedance characteristics of the balun. The example below describes the procedure in detail.

balun is found by measuring the open-circuit impedance. At 45 MHz, the balun described is $160\Omega \angle -85^\circ$. To determine the significance of the shunt impedance of the device under measurement, the $160\Omega \angle -85^\circ$ impedance must be rotated toward the load 0.06λ. After rotating $160\Omega \angle -85^\circ$ toward the load 0.06λ, the impedance shunting the balanced terminals is $550\Omega \angle 75^\circ$ as read on the $Z \angle\Theta$ Chart. Therefore, any mea-

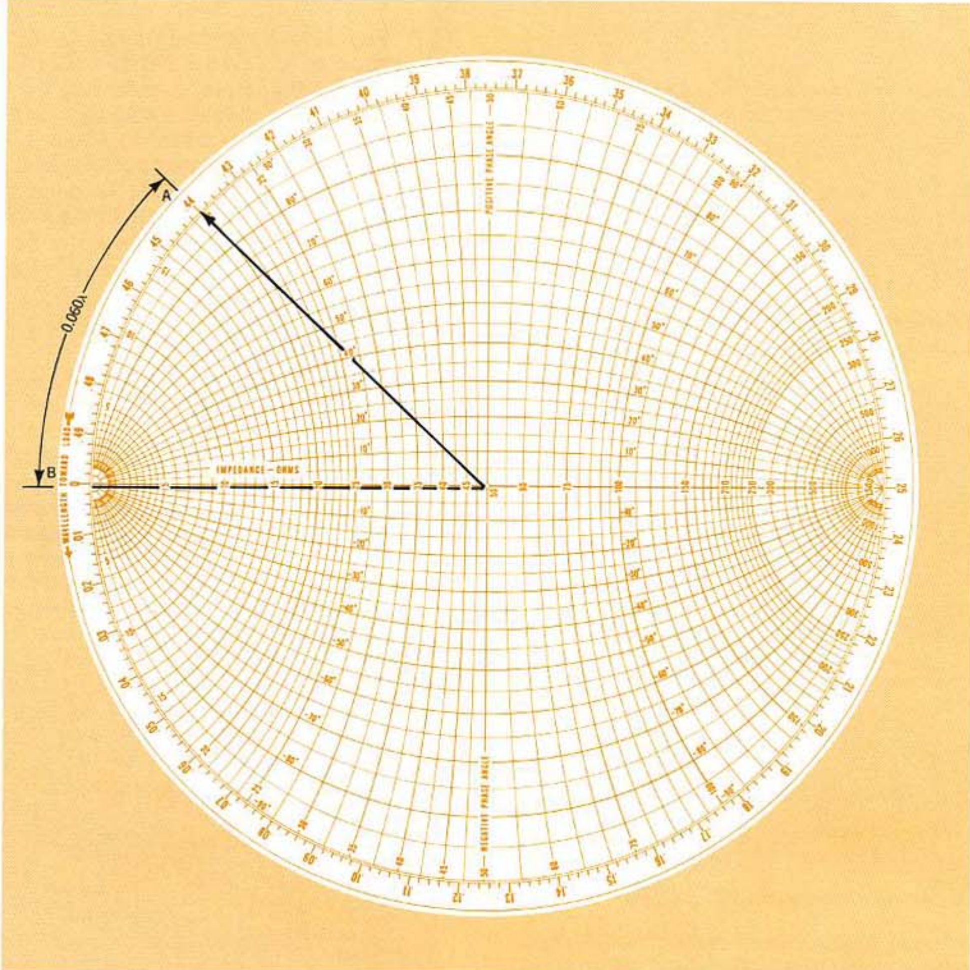


Fig. 11. Z/θ Chart showing determination of wavelength of balun at 45 MHz.

Referring to the $Z \angle\Theta$ Chart in Figure 11, the following steps are necessary to determine the wavelength of the balun at 45 MHz. First, the balun is shorted. Under shorted conditions, the impedance meter reads 20Ω at an angle of 90°. This point is then located on the $Z \angle\Theta$ Chart as point A. Next, since a short applied directly to the impedance meter probe ideally should read 0Ω at an angle of 0°, this point should be located as point B. Finally, the wavelength of the balun is determined by reading the difference in wavelength between points A and B on the $Z \angle\Theta$ Chart. At 45 MHz, the balun described has a wavelength of 0.06λ. Each impedance measurement made with the balun at 45 MHz should be rotated 0.06λ toward the load to correct for the impedance transformation due to balun wavelength. The correction must be determined for each measurement frequency.

Besides correcting for the wavelength of the balun, a correction for the shunt impedance effect may also be necessary. The shunt impedance of the surement made using the balun is shunted by $550\Omega \angle 70^\circ$. Therefore measurements made with the balun require two corrections.

The procedure for making a measurement at 45 MHz with these corrections is as follows. First, measure the device under test with the balun, locate this point on the chart and rotate 0.06λ back toward the load. Second, correct for the effect of the balun shunt impedance by converting to admittance and Cartesian coordinates and subtracting the admittance of the balun. Reconverting to impedance will yield the corrected balance measurement of the device under test. If the impedance of the device under test is appreciably less than the impedance of the balun, the shunt effect of the balun may be insignificant and therefore ignored for this measurement.

To measure the effectiveness of the balun, one terminal should be shorted and the other opened. The impedance is then measured. Next, the short is switched to the open terminal and the impedance is again read. At the frequency of application, these two impedance readings should agree. At 45 MHz, the balun measured 174Ω $\angle -84^{\circ}$ and 173Ω$\angle -84^{\circ}$ respectively. The frequency range is determined by the effectiveness of the balun. By adding more toroids, the low-frequency balance can be improved.

SECTION IV
TRANSFORMER MEASUREMENTS

One of the more sophisticated capabilities of the Vector Impedance Meters is the capability to quickly characterize transformer and servo motors. The following paragraphs describe measurements with a typical audio transformer (Figure 12) using the 4800A. The vector impedance characteristics of this transformer are shown in Figures 13 and 14.

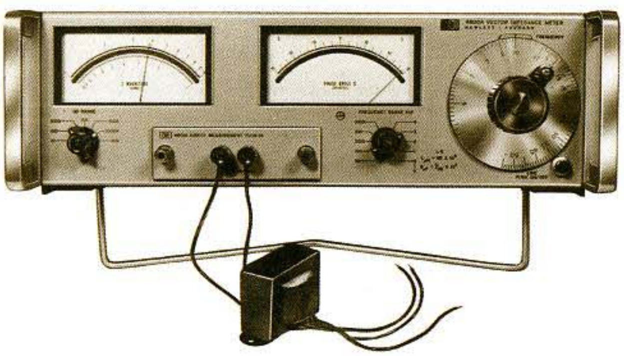


Fig. 12. A number of transformer parameters may be determined with both Vector Impedance Meters. An iron-core transformer, used at lower frequencies, may be quickly characterized using the 4800A.

A plot of vector impedance, as a function of frequency, is probably the most complete data that can be given for a transformer under any given operating conditions. Referring to the plots in Figures 13 and 14, several significant facts can be obtained. First, the bandwidth can be found from the 45° phase points which occur at 180 Hz and 40 kHz. Next, the impedance over the entire band can be checked for both phase and magnitude variations. The magnitude varies from 900 ohms to 2400 ohms about a mid-range value of 1300 ohms. Similarly, the phase varies some 35° about a mid-range phase of 10°. Phase variation over the bandwidth will cause phase distortion in the audio signal. Also, a high-impedance resonance occurs at 18 kHz.

Referring to Figure 15, measurements that can be made include the primary inductance, primary resistance, primary capacitance, secondary inductance, secondary resistance, secondary capacitance, leakage inductance, mutual inductance, primary-to-secondary capacitance, and turns ratio.

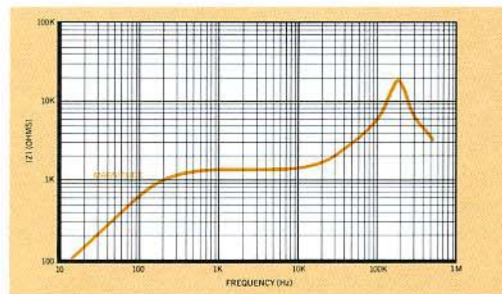


Fig. 13. Plot of impedance as a function of frequency for an iron-core audio transformer terminated in 8 ohms.

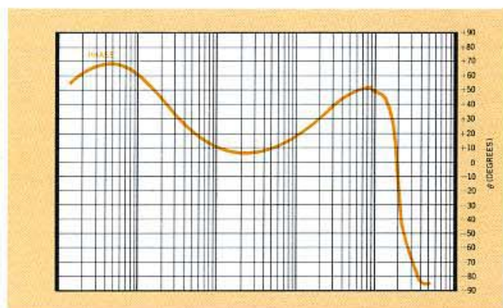


Fig. 14. Plot of phase as a function of frequency for an iron-core audio transformer terminated in 8 ohms.

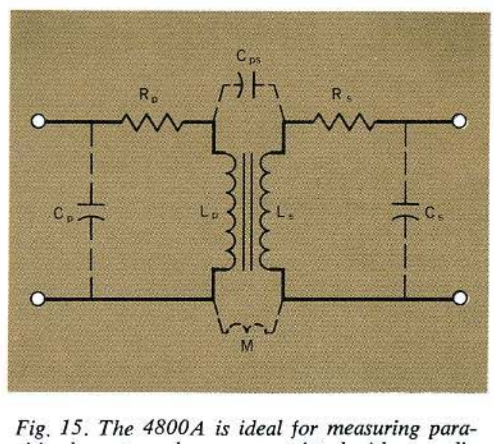


Fig. 15. The 4800A is ideal for measuring parasitic elements such as are associated with an audio transformer.

PRIMARY INDUCTANCE, RESISTANCE, AND CAPACITANCE

To measure the primary inductance, resistance, and capacitance, the primary is connected to the 4800A terminals and the secondary is left open. The frequency is adjusted so that the impedance is inductive, as indicated by a phase of approximately 90^{o}. Using a frequency that is a decade multiple of 15.9, as marked by the LC inscription on the dial, the inductance is read directly.

$$\theta = 88^{o}$$
$$f = 15.9 \times 10 \text{ Hz}$$
$$|Z| = 1.02 \times 1K\Omega$$
$$L = 1.02 \text{ H}$$

The dynamic resistance in the primary is determined at the lowest measurement frequency where the phase angle is 60^{o}. Since it is usually impossible to find a low frequency within the frequency range of the 4800A, where the phase angle is 0^{o}, it is best to use a convenient angle such as 60^{o}. At this phase angle, the resistance equals 1/2 the total impedance. Thus, the resistance is 1/2 the impedance read on the Z magnitude meter.

$$\theta = 60^{o}$$
$$f = 8.3 \text{ kHz}$$
$$|Z| = 4.1 \times 10K\Omega$$
$$R_p = |Z|/2 = 2.05 \times 10K\Omega = 20.5K\Omega$$

The primary capacitance is determined by selecting a frequency at which primary inductance and capacitance resonate. For the purpose of these measurements, resonance is defined by a phase angle of 0^{o}. Since the inductance and the frequency are known, the transformer capacitance is calculated from the formula:

$$C = \frac{1}{\omega^2 L}$$

or found on the Vector Impedance Calculator described in the Appendix.

$$\theta = 0^{o}$$
$$f = 18.5 \times 1 \text{ kHz}$$
$$L = 1.02 \text{ H (as previously determined)}$$

$$C = \frac{1}{(2\pi f)^2 L}$$

$$= \frac{1}{(2\pi\, 18.5 \times 10^3)^2\, 1.02}$$

$$= 76 \text{ pF}$$

If the resonance frequency is beyond the range of the 4800A, an external capacitor of known value can be connected in parallel with the primary and the shunt subtracted from the above calculated capacitance.

SECONDARY INDUCTANCE AND RESISTANCE

The inductance and resistance of the secondary are measured following the same procedure used with the primary, except that the secondary is connected to the 4800A terminals and the primary is left open. The results are as follows:

$$L = 16.3 \text{ mH}$$
$$R_p = 6.6 \times 100\Omega$$

TURNS RATIO

The turns ratio is quickly approximated by using the impedance transfer properties assuming tight coupling; i. e., $K \approx 1$. A resistor, R, will read an impedance of Z when connected across the secondary and measured from the primary. The ratio of R to Z is related to the turns ratio:

$$N^2 = \frac{R}{Z}, \text{ where } N = \frac{\text{number secondary turns}}{\text{number primary turns}}$$

For best results, R should be much less than the primary reactance. The phase should be approximately zero to assure that the reflected impedance has no reactive component.

The following results were obtained from the transformer in Figure 12.

$$\theta = 0^{o}$$
$$|Z| = 4.9 \times 1K\Omega$$
$$R = 100\Omega$$

$$N = \left(\frac{R}{Z}\right)^{1/2} = \frac{1}{7}$$

MUTUAL INDUCTANCE

Mutual inductance is determined by measuring the transformer inductance in series aiding and series opposing configurations, subtracting the smaller inductance from the larger, and then dividing the remainder by four.

$$M = \frac{L_{aiding} - L_{opposing}}{4}$$

	Opposing	Aiding
θ	86^{o}	88^{o}
f	159.2 Hz	159.2 Hz
|Z|	$7.6 \times 100\Omega$	$1.25 \times 1K\Omega$
L	760 mH	1250 mH

$$M = \frac{1250 - 760}{4} = 123 \text{ mH}$$

LEAKAGE INDUCTANCE

Leakage inductance is determined by shorting the secondary and measuring the impedance of the primary.

$\theta = 81^{o}$
$f = 15.9$ kHz
$|Z| = 14\Omega$
$L = 140\ \mu H$

If the leakage reactance is too small to be read directly on the 4800A meter, a capacitor that will resonate with the leakage inductance can be connected across the primary. The leakage inductance is then calculated from the formula:

$$L = \frac{1}{\omega^2 C}$$

or from the Vector Impedance Calculator.

With iron core transformers, a dc component can be injected into the primary or secondary. Appropriate dc blocking capacitors are necessary with the 4800A. (See Figure 16). Inductance as a function of dc current can then be measured.

PRIMARY-TO-SECONDARY CAPACITANCE

Primary-to-secondary capacitance is measured by connecting one lead of the primary and one lead of the secondary to the terminals of the Vector Impedance Meter. The other leads may be open or shorted. Phase angle should be approximately -90^{o}.

$\theta = -88^{o}$
$f = 159.2$ Hz
$|Z| = 7.2 \times 1$ megΩ
$C = 137$ pF

SECTION V
MEASUREMENTS INVOLVING DC BIAS

It is frequently necessary to make impedance measurements in the presence of dc bias. Measurements on both diodes and transistors are common examples of this requirement. The 4815A can be used directly for these measurements providing the bias voltage is less than 50 volts. Above 50 volts, blocking techniques must be used to prevent the dc voltage from entering the probe.

Unlike the 4815A, the 4800A must have no dc bias signal applied directly to the terminals since they are connected directly to the amplifier channels. However, bias measurements are possible if the dc is properly blocked. The circuit in Figure 16A shows one way to apply a bias. A blocking capacitor prevents dc from flowing through the 4800A. The impedance of the capacitor must be small compared to that of the device under test. This can be verified with the 4800A. Since the dc bias supply appears in parallel with the unknown, the impedance of this portion of the circuit (dc supply plus its associated resistor) must have a high value with relation to the unknown. If this condition cannot be achieved, the power supply impedance will reduce the observed value of the unknown to be measured. These readings can be corrected, however, by making a separate measurement of the dc supply impedance and manually correcting the data.

The dc supply must be ungrounded unless the regulating resistor (R) is very large. A large resistance with grounded supplies will isolate the 4800A test signal from ground. See Figure 16B.

The blocking technique described above can be used to measure the dynamic impedance of a diode. By biasing the diode from a known dc current source, the impedance can be recorded as a function of current. If the diode is back biased, the junction capacitance, as a function of voltage, can be measured.

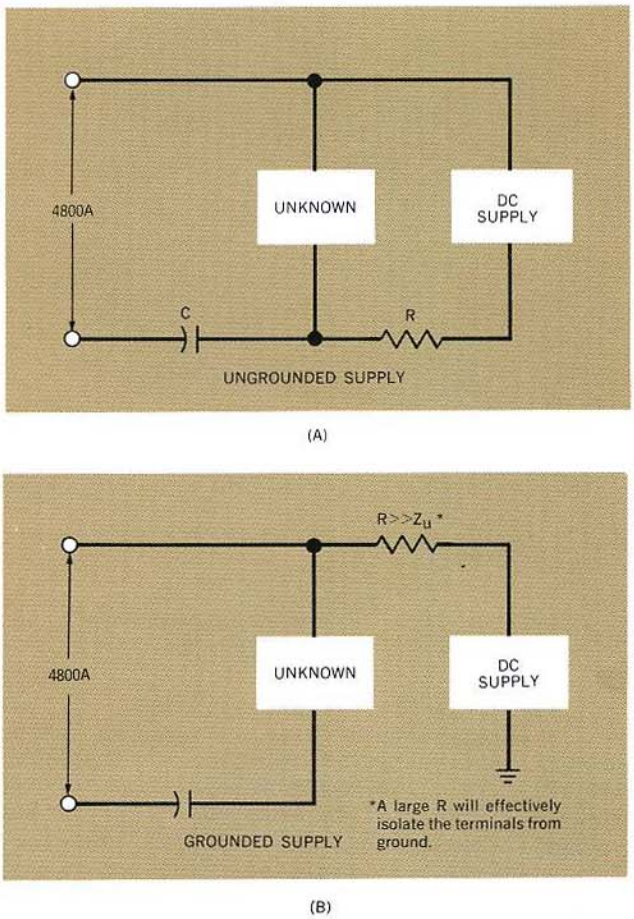


Fig. 16. Blocking circuit to keep dc from 4800A amplifier circuit. 4815A is ac coupled with capacitor in probe.

Voltage-variable capacitors and current-variable inductors can be measured in a similar manner.

VARACTOR JUNCTION CAPACITANCE

Figures 17 and 18 illustrate the measurement of varactor junction capacitance as a function of voltage. The 4800A is operated at 159.2 kHz so that capacitance may be read out directly in picofarads. A 419A Voltmeter is used to set the bias level across the varactor.

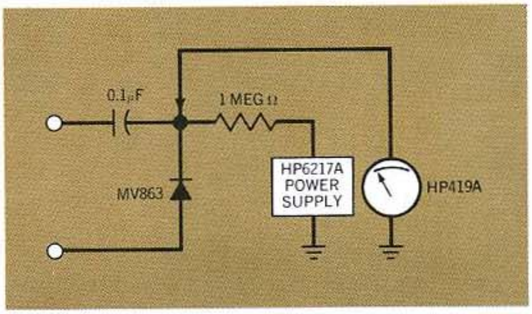


Fig. 17. Setup for measuring varactor junction capacitance as a function of voltage.

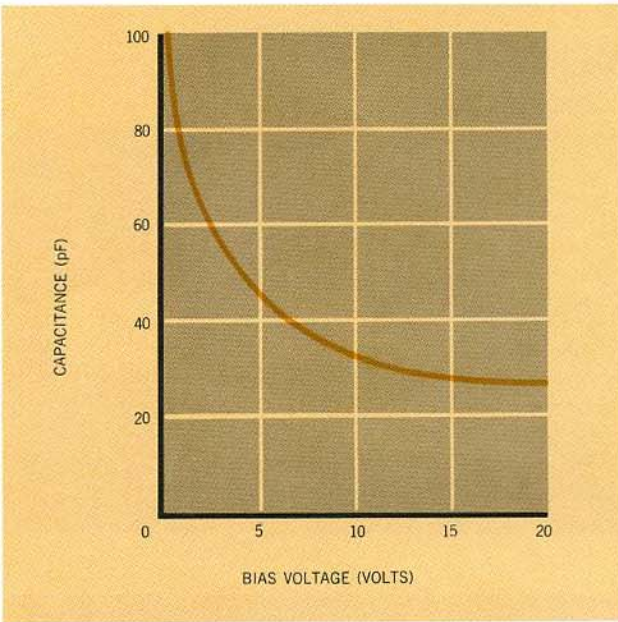


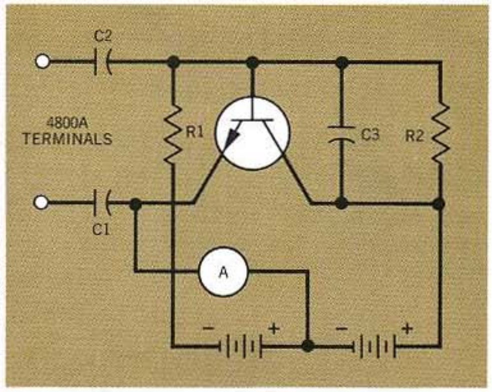
Fig. 18. Junction capacitance of a varactor as a function of bias voltage. $f = 159.2$ kHz.

TRANSISTOR BIASING

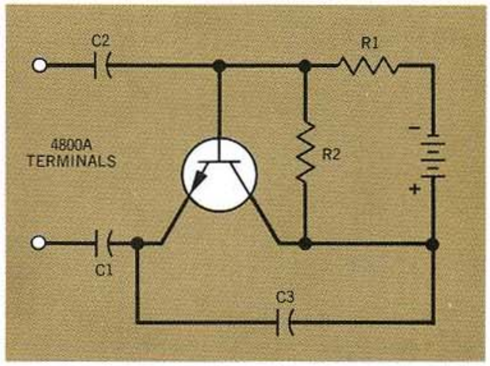
The biasing scheme shown in Figure 19A may be used to measure h_{ib} of a transistor. By connecting the circuit as shown in Figure 19B, the instrument will measure h_{ie}. If the same biasing current and voltage are used for both the h_{ib} and h_{ie} measurements, beta can be approximated from the expression:

$$h_{fe} = \frac{h_{ie}}{h_{ib}} - 1$$

The above expression assumes that h_{re} is negligible. For measurements at the 4800A frequencies, the assumption is generally valid.



(A)



(B)

Fig. 19. Using an appropriate biasing scheme (A), it is possible to measure h_{ib} of a transistor. By reconnecting the circuit as in (B), the instrument will measure h_{ie}. C_1 and C_2 are dc blocking capacitors. R_1 and R_2 are bias resistors.

LARGE ELECTROLYTICS

A problem that often arises when measuring large capacitors with a bias is finding a larger capacitor for blocking. The blocking capacitor need not be significantly larger if one is willing to do some brief calculation. The following example demonstrates the technique for measuring a 67 μF electrolytic capacitor biased by 45 volts.

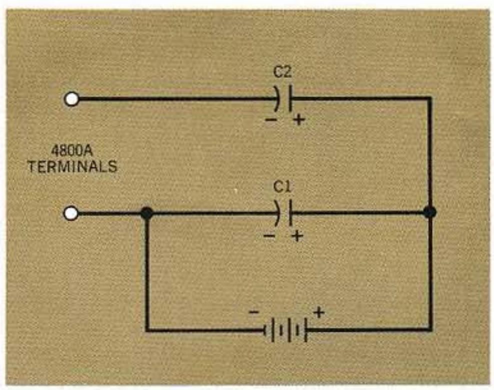


Fig. 20. Large electrolytic capacitors may be measured by connecting two capacitors in series, then biasing.

The "unknown" 67 μF capacitor is connected in series with a similar capacitor of approximately equal value. The negative terminals are connected to the

4800A and the positive terminals joined. A 45-volt battery is connected across the "blocking capacitor" with regard to the correct polarity, Figure 20. Under these conditions, equal voltage appears across each capacitor. However, the net voltage between the 4800A terminals is zero.

The Z magnitude meter reads the series combination of C1 and C2.

$$|Z| = X = \frac{1}{\omega C_T}$$

$$C_T = \frac{1}{\omega |Z|} = \frac{C_1 C_2}{C_1 + C_2}$$

$$C_2 = \frac{C_T C_1}{C_1 - C_2} = \frac{\frac{-C_1}{\omega |Z|}}{C_1 - \frac{1}{\omega |Z|}} = \frac{C_1}{\omega |Z| \; C_1 - 1}$$

If the blocking capacitor is selected to be at least ten times greater than the unknown, the term $\omega |Z| \; C1$, is large compared to one. The equation then becomes:

$$C_2 = \frac{1}{\omega |Z|}$$

When working with a biased capacitor, use extreme caution. A charged capacitor, placed directly across the terminals of the 4800A, can discharge enough current to damage the diodes in the instrument.

Varactors can also be measured by placing them in series. Figures 21 and 22 illustrate the series measurement of two MV863 varactors. These results should be compared to the above results obtained with one MV863.

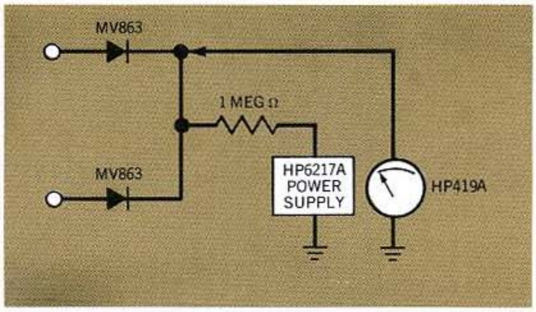


Fig. 21. Setup for series measurement of varactors.

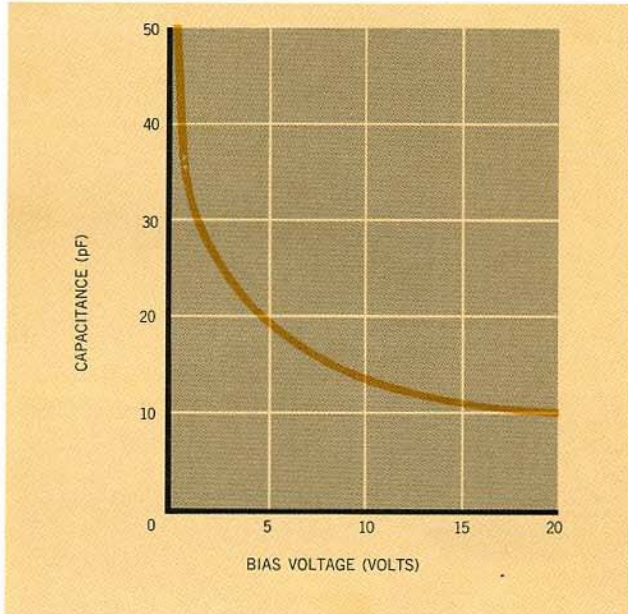


Fig. 22. Junction capacitance of two series varactors as a function of bias voltage. f = 159.2 kHz.

GROUNDED MEASUREMENTS

Grounded measurements with the 4800A are a special case and are generally not recommended. A simplified block diagram of the 4800A circuit, Figure 23 will point out the reason for this. If a terminal is grounded, either the oscillator or the current channel is shorted. If the secondary of an isolation transformer is connected across the terminals, the grounded unknown may be placed across the primary. However, transformers are generally restricted to narrow ranges of impedance and frequency.

Measurement Condition	4800A	4815A
DC bias	A suitable blocking capacitor is necessary to prevent DC from entering the terminals. Choose a capacitor that has negligible impedance compared to the unknown. Be sure it is discharged before connecting it to the terminals.	The probe contains a blocking capacitor sufficient to block 50 volts dc. Use external blocking above 50 volts.
External Signal (AC or Noise)	Although the internal circuitry is broadband from 5 Hz to 500 kHz, each frequency range has bandpass filtering. An external signal, 2 decades from the measurement frequency, is attenuated at least 14 dB. External interference will cause the phase and magnitude needles to swing wildly.	The external signal could beat with harmonics of sampling rate which varies from 0.5 to 1 MHz in spacing. The interference will cause the phase and magnitude needles to swing wildly. By resetting the frequency slightly, the interference can often be effectively filtered.

Table 3. Measurements with ac bias or external signal.

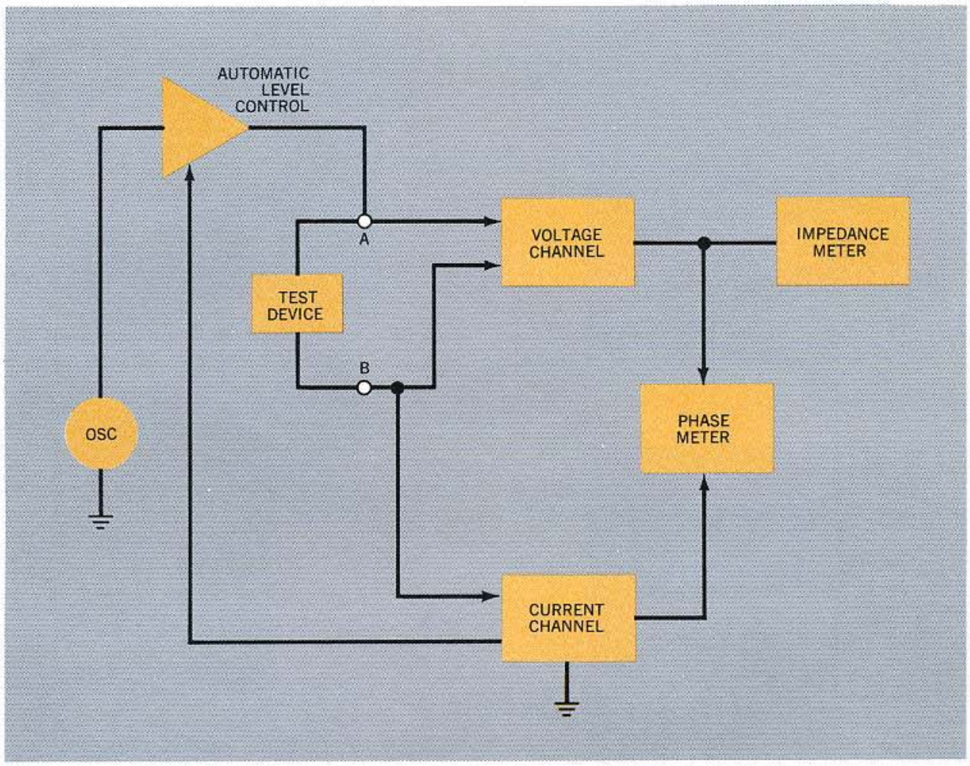


Fig. 23. Simplified Block Diagram — Vector Impedance Meters.

SECTION VI
MEASUREMENTS WITH AC OR NOISE SIGNALS PRESENT

Generally, measurements with external ac or noise present require the use of careful techniques. The impedance measuring circuits of both instruments behave as high-gain voltmeters. Thus, it is possible to have an external unwanted signal amplified to the same order of magnitude as the internal test signal of the Vector Impedance Meter. This situation will, of course, result in a completely spurious impedance reading. The condition is generally easy to recognize, however, since it almost always results in a complete inability to obtain a stable on-scale reading of either impedance or phase, or both. Since both Vector Impedance Meters have an internal oscillator that excites circuits under test through the measuring terminals, it is not necessary to have another ac source present to make measurements. In measurements where interfering noise is likely, such as with antennas, electrical isolation of the measuring setup is often necessary. In addition, devices which have the property of converting some other parameter to electrical energy must be isolated from that type excitation. For instance, a piezoelectric transducer may have to be isolated from mechanical vibration to prevent the generation of unwanted ac signals.

Each Vector Impedance Meter is susceptible to interfering signals and noise in a different way. The 4800A is a broadband instrument over a continuous range of frequencies with an internal amplifier system that is flat from 5 Hz to 500 kHz. To help eliminate interference, bandpass filtering is used over each decade range of frequency. The interference can sometimes be effectively filtered by choosing a freqquency two decades away from interference.

The 4815A, on the other hand, uses a unique technique of synchronous sampling to convert the RF to a 5 kHz IF. Although the IF has a narrow bandwidth of 120 Hz, interference at either the fundamental or harmonics of the sampling rate is converted to the IF frequency. Consequently, the 4815A can be considered as a narrow-band instrument at discrete frequencies. Depending on the frequency of measurement, the sampling harmonics will occur at intervals spaced up to 1 MHz apart over the entire 0.5 to 108 MHz range. Thus, the instrument is susceptible to interference from broadband noise. The conditions under which measurement in the presence of noise can be made are discussed in the following paragraphs. It should be remembered that a limitation of 50 volts dc at the probe tip must not be exceeded.

At the frequency of the test signal, the probe of the 4815A appears to be a constant-current source; at all other frequencies, it appears to be an essentially resistive impedance of approximately 25 ohms. Assuming that the interfering signal is not at the frequency of the test signal, there are two ways in which it may interfere with the measurement. First, it may overload the input sampler and produce intermodulation. This will occur if the unwanted signal amplitude is greater than 0.5 volts rms into 25 ohms.

Second, the interfering signal may beat with a harmonic of the sampling rate and produce a spurious IF signal. If the unwanted signal is an unmodulated carrier, the beats will be observed as the 4815A is swept in frequency. The measurement can be made by tuning the 4815A test signal frequency to a point between the beats. This technique can be used when measuring the impedance of a mixer with the local oscillator excitation applied. If the signal is modulated (particularly frequency or phase modulated), the chance of beating is greatly increased, and it may be impossible to find a point at which interference is not occurring. In this case, the measurement cannot be made accurately (or at all), depending on the severity of the interference. This condition can be recognized by extremely noisy meter indications and/or wild variations in impedance with minute changes in test signal frequency, and/or complete lack of range-to-range tracking of the impedance magnitude scales. Wide-band noise presents the same difficulties as a frequency or phase modulated signal, since the number of interfering frequencies is infinite. In this case, the measurement can be made only if the magnitude of the noise signal is small compared to the test signal level.

For the case where the interfering signal present in the circuit is at exactly the same frequency as the test signal, the measurement will be essentially meaningless since the signal will be converted to IF as discussed under the second condition above. One exception to this rule is the case of measurements within the feedback loop of an oscillator. If the source impedance of the loop is large compared to 25 ohms at the point of measurement, loading of the probe will stop oscillation. The impedance observed will have a negative real part (negative resistance component), since the oscillator is supplying power to the probe. The frequency at which the phase angle is 180° is the frequency of oscillation. The magnitude of the negative resistance varies inversely with the amount of positive feedback. This particular application is discussed in detail in the section on active circuit measurements.

TRANSDUCER MEASUREMENTS

There is an application for the Vector Impedance Meters in the measurement of transducer parameters. Sonic transducers are one example. Some precautions must be taken in making these measurements, however, since transducers are often broadband devices and may pick up noise very effectively. This incoming noise may saturate the measuring circuits making it impossible to get on-scale indications. Mechanical and acoustical isolation of the device to be measured is often required to obtain useful results. Generally, when noise is a problem, the result is complete inability to make measurements, rather

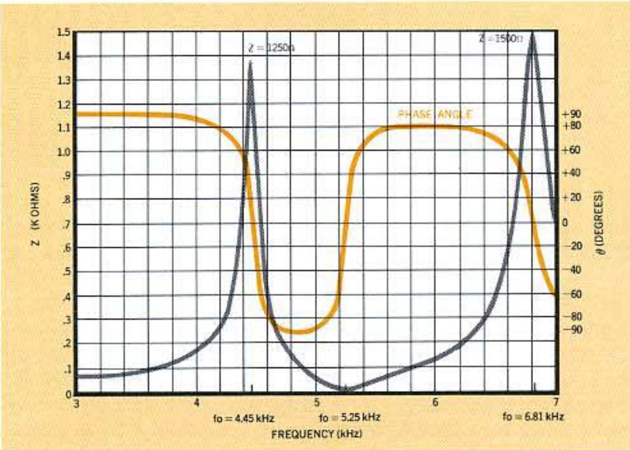


Fig. 24. Plot of impedance and phase as a function of frequency for a hydrophone.

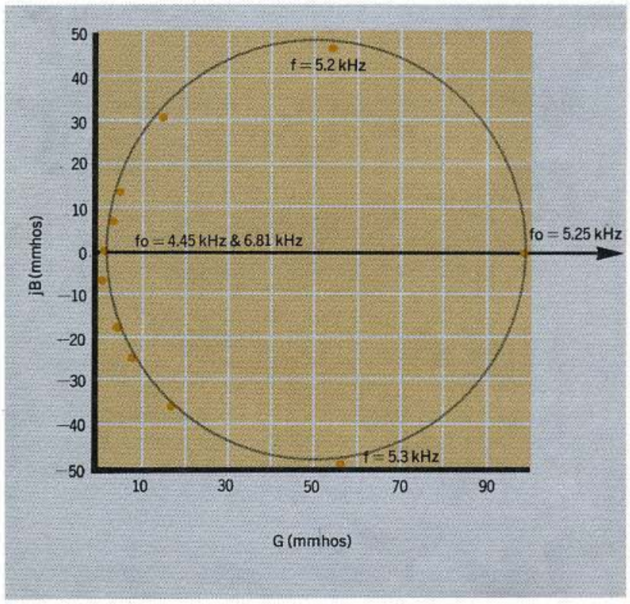


Fig. 25. Locus of jB as a function of G for a hydrophone.

than erroneous readings. The advantage of the Vector Impedance Meters in this application is, of course, the capability to characterize the transducer over its entire operating frequency range, quickly and easily.

Many transducer plots are expressed in terms of R and jX or G and jB, rather than Z and Θ. If R and X are the desired quantities, they may be manually replotted from a $Z \angle \Theta$ plot by resolving the rectangular coordinates. The general shape and discontinuities on the $Z \angle \Theta$ curve will determine the points that should be more closely examined on an R + jX plot. Similarly, G and jB may be manually replotted using the reciprocal of Z to obtain Y, taking the negative of the phase angle reading, and resolving Y into the rectangular coordinates. Figures 24 and 25 show data taken with the Model 4800A from a hydrophone used for detecting underwater noises. The data was taken with the hydrophone unloaded; i.e., in air, although similar data can be obtained with the unit immersed in water. In general however, this is a laboratory measurement since there is normally an excessive amount of interfering signal present in field measurements.

MEASUREMENT OF MIXER INPUT AND OUTPUT

It is also possible to measure the input and output impedance of a mixer while it is being excited with the local oscillator. However, special care must be taken to select a measuring frequency such that the 4815A test signal will not mix with the local oscillator signal, thus, producing an error signal. Suitable measuring frequencies can be determined empirically while making the measurement. Since an interfering error signal is extremely sensitive to the measurement frequency, the measured impedance will exhibit large variations for very small frequency deviations when an interfering signal is causing an error. Between any two successive frequencies producing an error signal, there should be a range of frequencies for which the measured impedance is essentially constant. The impedance measured within this "constant" range is the correct value.

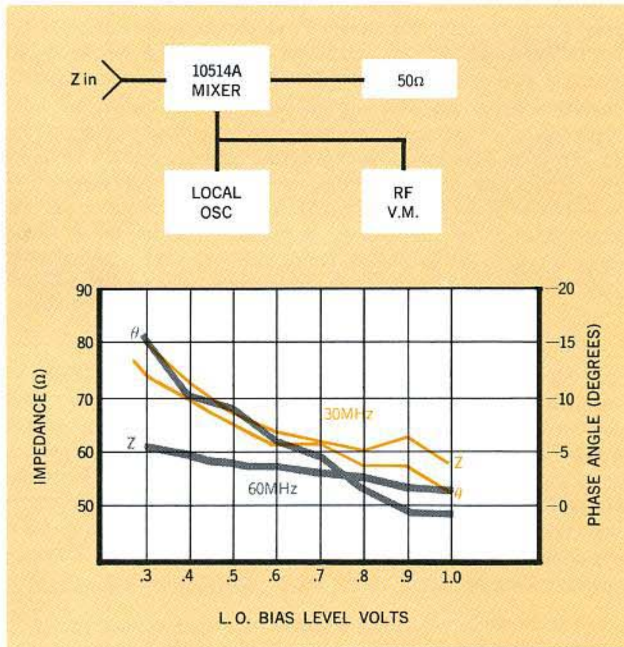


Fig. 26. Input impedance to a 10514A Mixer as a function of local oscillator bias.

Figure 26 shows typical data obtained from the -hp- Model 10514A Mixer. The input impedance, as a function of local oscillator bias level, is plotted for a measuring frequency of 30 MHz. It can be seen that the VSWR of the mixer improves from 1.6 to 1.02 as the bias level is varied. In addition, one may examine the effect of changing the loading, at the third port of the mixer, to values other than 50 ohms. Thus, it is possible to quickly examine the impedance at each port of the mixer and to determine the compensation necessary for establishing conjugate matches.

SECTION VII
ACTIVE CIRCUIT MEASUREMENTS

The accuracy and flexibility of the Vector Impedance Meters in making passive circuit measurements are also realized in the case of active circuits. However, two considerations must be taken into account. First, care must be taken to exclude both ac and dc signals from the measurement. (See Sections V and VI). Second, the test signal level of the Vector Impedance Meters must be within the linear region of the circuit, since impedance is defined only for linear circuits. Also, it should be remembered that measurements on the 4815A are referenced to ground, while the 4800A makes ungrounded measurements. The in-circuit probe (Figure 27) makes the 4815A especially applicable to active circuits.

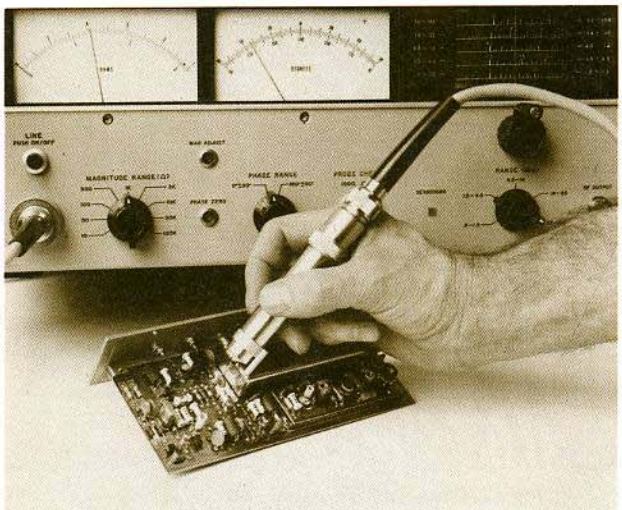


Fig. 27. The 4815A probe makes possible direct in-circuit measurements of vector impedance.

The second consideration of possibly driving the circuit into a nonlinear region is unlikely to cause problems since the test signal is deliberately kept small. The 4815A injects a constant current of 4 μA, except on the 10 ohms full-scale range where it is 12.6 μA. Therefore, the voltage across the unknown is dependent on the impedance magnitude. The 4800A injects a constant current of 270 μA on the X10 range, and 270 μA on the X100 range. On the X1K range, a constant voltage of 2.7 mV is applied, on the X10K it is 27 mV, on the X100K it is 207 mV, and on the X1M it is 2.7 V. Thus, the voltage or current respectively is constant, depending on the impedance range.

Measuring the input impedance of an amplifier is one example where it is first necessary to decide whether the signal level will overdrive the circuit. Should the input characteristics of the circuit be known, observing the output on an oscilloscope may be helpful. In general, the problem arises only with amplifiers having a combination of high input impedance and high voltage gain. With the 4800A, high-gain circuits with low input impedance might be overdriven on the constant-voltage ranges.

As an example of active circuit measurements that may be made with the 4815A, consider the tuned amplifier circuit in Figure 28.

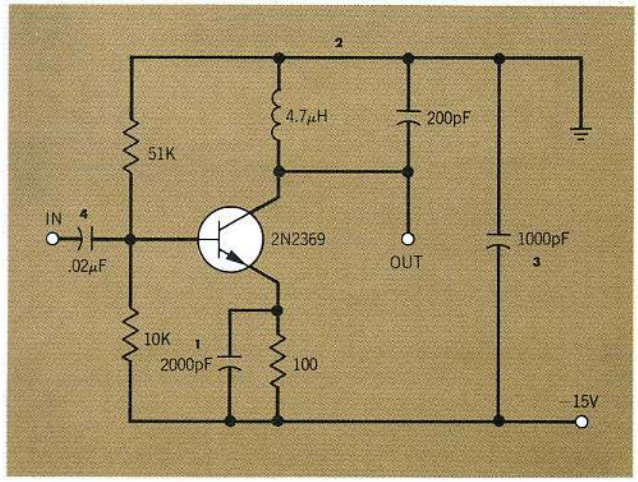


Fig. 28. 5 MHz tuned amplifier shows negative resistance from 4 MHz to 6 MHz.

Some of the measurements which can be made on the circuit are:

1. The effectiveness of the bypass capacitor. - It may be desirable to choose a capacitor which is series resonant at the operating frequency. This can be done quickly with the 4815A.
2. The resonant frequency and Q of the tank circuit. - One great advantage of the 4815A is that this measurement can be made "in-circuit" with all loads connected.
3. Output impedance.
4. Input impedance of the amplifier. - See Fig. 29.

The real advantage of the Vector Impedance Meters in this type application is that the various parameters may be measured and the effects of circuit changes or compensation may be directly observed as they are accomplished. In addition, variations as a function of frequency can be quickly verified.

For the particular circuit configuration shown in Figure 28 for instance, examination of the input impedance provides extremely valuable information about circuit performance that is not readily available through any other measurement technique. In this circuit, the IF amplifier is required to operate at 5 MHz. However, when the input impedance is measured over the range from 4 to 6 MHz, it is found to exhibit an impedance having a phase angle in the third quadrant of the complex impedance plane. Figure 29 graphically illustrates the input impedance of the IF amplifier as a function of frequency. In this case, the

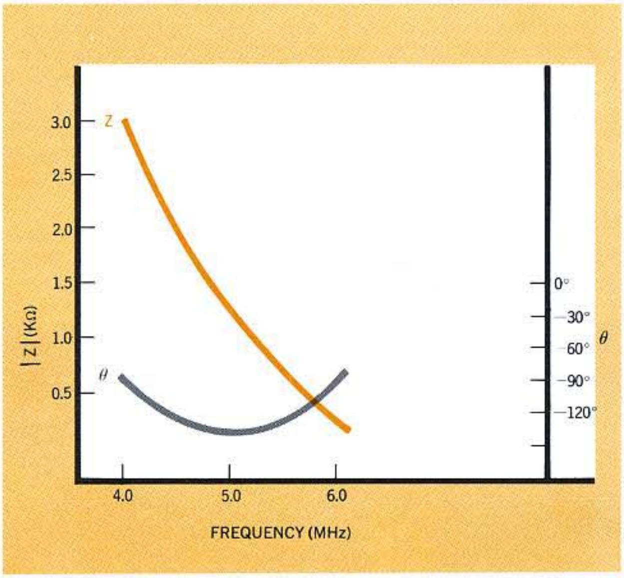


Fig. 29. Amplifier input impedance — tuned 5 MHz.

amplifier will be unstable and could oscillate with inductive sources. For example, a mixer might logically cause the circuit to oscillate. In order to achieve stable design, neutralization may be required. Effectiveness can be evaluated directly with the 4815A.

Another example of the type circuit measurements possible with the 4815A is illustrated by a low-frequency oscillator such as the one shown in Figure 30. Since this circuit is regenerative, its natural oscillation must be damped so that an impedance measurement is possible. Otherwise, the 4815A reading will be meaningless. This is easily achieved with the 4815A in this particular circuit since the input impedance of the probe is 25 ohms. The 25-ohm impedance loads the tank circuits, lowering the effective loop gain and preventing oscillation. Yet, the constant-current characteristics of the probe permit an accurate measurement of the circuit impedance.

Measurement of this impedance is useful in predicting gain variation with frequency. The measurement is accomplished by tuning the oscillator to various frequencies and measuring the tank circuit. Referring to Figure 30, the oscillator is tuned by adjusting the 8 to 200 pF capacitor. Impedance measurements are made by placing the probe between the transistor collector and ground. The 4815A should be set to the frequency of oscillation. When the frequency is properly set, the phase angle will be 180°, indicating a pure resistance acting as a source impedance. Variation of this resistance over the frequency range is a direct measurement of the variation in gain, and the tank circuit impedance may be adjusted or optimized to keep it within the desired limits. Figure 31 shows data taken on this oscillator circuit.

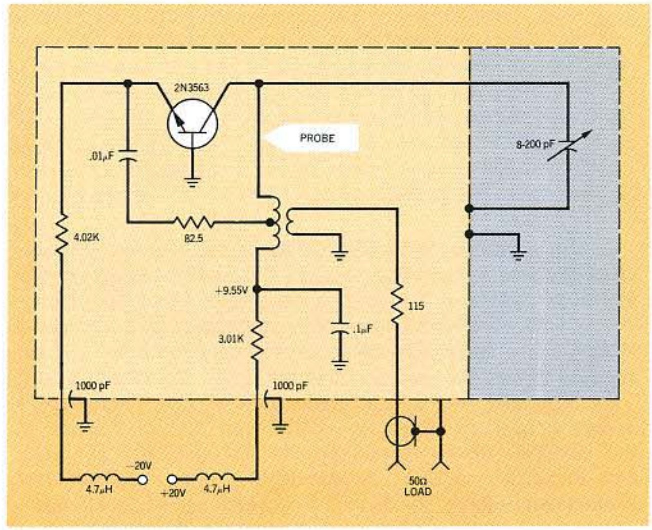


Fig. 30. Low-frequency oscillator.

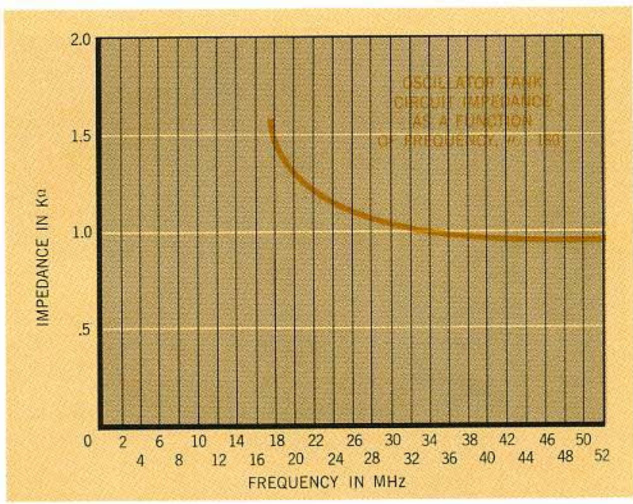


Fig. 31. Circuit impedance as a function of frequency.

SECTION VIII
X-Y PLOTTING

Both the 4815A and the 4800A can be used with an X-Y recorder to obtain continuous records of impedance and phase as a function of frequency. The analog outputs on the rear panel of the Vector Impedance Meters produce a voltage proportional to the impedance meter deflection, phase meter deflection, and frequency dial position. These analogs can also be used to obtain impedance and phase as a function of other parameters, such as bias current. Besides being used for recording purposes, the analog can be used in conjunction with an -hp- Model 3440A Digital Voltmeter to produce a digital readout for greater resolution. The 4800A combined with the -hp- Model 3434A Comparator makes an ideal go-no-go impedance checkout system.

The Vector Impedance Meters can be frequency swept either mechanically or electronically. To sweep the instruments electrically, the rear panel oscillator loop should be disconnected and a suitable sweep oscillator should be connected to the external oscillator input. All range switches, including the frequency range switch, must be set to the correct range.

The swept rate of the 4815A is limited by the tracking rate of its phase lock loop to 1 MHz per second. When sweeping either electrically or mechanically, the sweep rate must not exceed this tracking rate. If it does, the "search" light on the 4815A front panel will light.

The sweep rate of the 4800A is limited by the time constant of the automatic level control feedback circuit. Consequently, the maximum permissable sweep rate is a function of the impedance magnitude variation. Each full-scale impedance magnitude variation may be swept no faster than 2 seconds. In other words, a resonance curve that rises and falls over a full-scale impedance magnitude range, would require at least 4 seconds to sweep. See Figure 32.

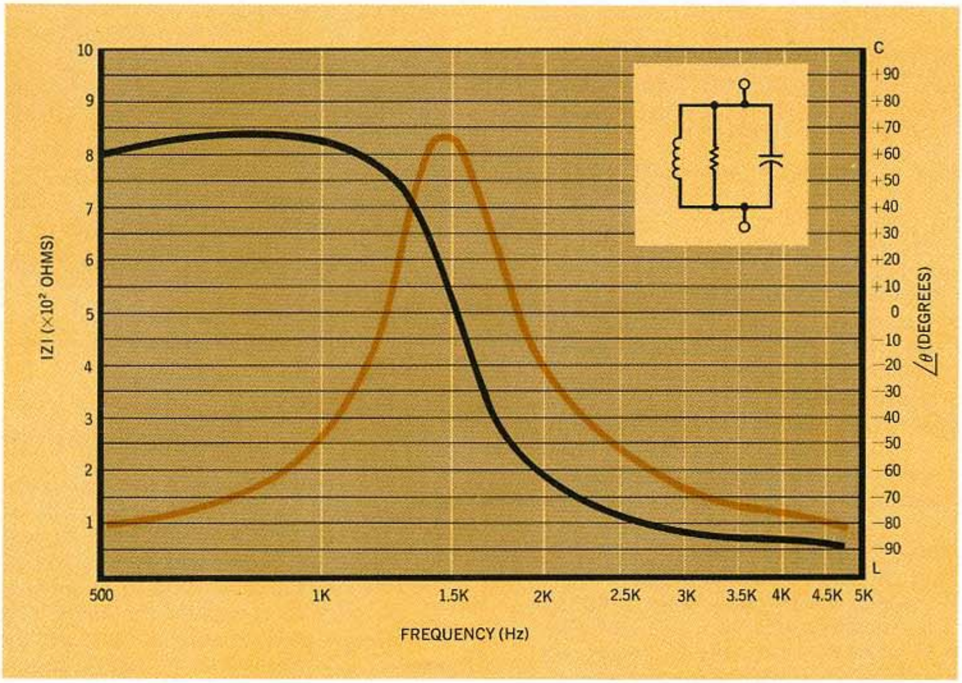


Fig. 32. Two-pen X-Y recording of tuned circuit.

GENERAL IMMITTANCE REVIEW

IMPEDANCE

A review of impedance will aid in the understanding of the Vector Impedance Meter operation and applications. The impedance of any finite, linear, passive, two-terminal, bi-lateral network can be represented by an equivalent parallel or series R, L, C network. Bridges are based on this principle in balancing the equivalent resistance or reactance of the unknown.

Impedance consists of two components; resistance and reactance. The resistive component dissipates electrical energy whereas the reactive component stores either electrical or magnetic energy. The reactive component can again be broken into two parts, inductance and capacitance. Since inductive reactance and capacitive reactance cancel each other, only the predominant one will be observed. Thus, the equivalent circuit will be either RL or RC, depending on the frequency.

The following formulas apply to the series equivalent circuit:

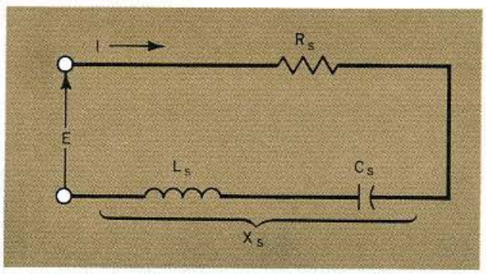


Fig. 33. Series equivalent circuit.

Resistance $= R_s$

Reactance $= X_s = \omega L_s - \frac{1}{\omega C_s}$; where $\omega = 2\pi f$

Impedance $= Z = E/I = R_s \pm jX_s = |Z| \angle\Theta$

where $j = 1 \angle 90^o$

+ indicates inductive reactance
- indicates capacitive reactance

$$\text{Impedance magnitude} = |Z| = \left(R_s^2 + X_s^2\right)^{1/2}$$

$$\text{Impedance phase} = \theta = \tan^{-1}(X_s/R_s) = \cos^{-1}(R_s/|Z|)$$

Impedance may be plotted in either polar coordinates (Z, $\angle\Theta$) or rectangular coordinates in the complex plane ($R \pm jX$).

The vector diagram for the series equivalent circuit is as follows.

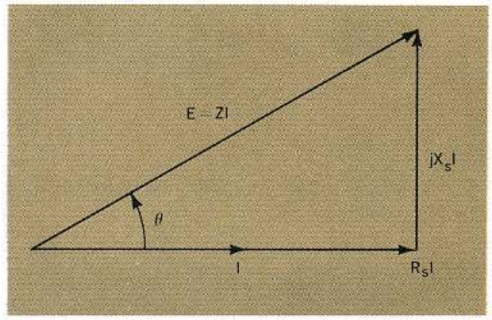


Fig. 34. Vector diagram for series equivalent circuit.

The diagram shows the voltage and current in phase for resistance. The voltage leads the current by 90^o (+j) for inductive reactance and lags the current by 90^o (-j) for capacitive reactance. Vectorially, the jX_s adds with the $-jX_s$ to yield either a net inductive or capacitive reactance. The phase Θ is the angle between the voltage across and current through the impedance $|Z| \angle\Theta$.

A series RLC circuit exhibits an impedance drop at resonance. The phase changes from -90^o to $+90^o$ as frequency increases.

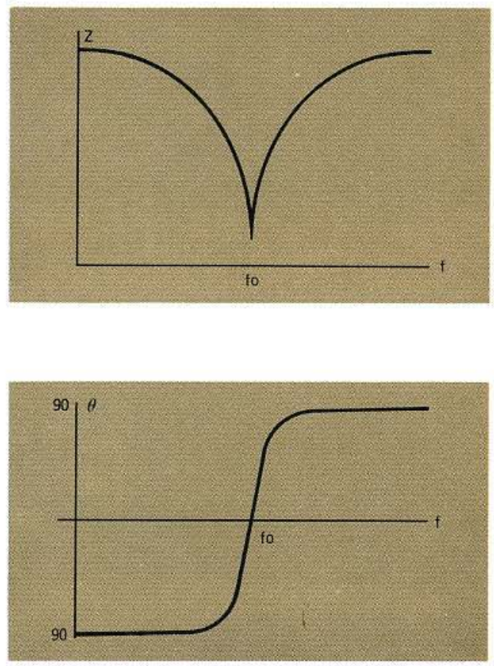


Fig. 35.

ADMITTANCE

Using the admittance parameters, an analogous set of equations can be written for the parallel equivalent circuit.

Conductance $= G = 1/R_p$

Susceptance $= B = \frac{1}{X_p} = \omega C_p - \frac{1}{\omega L_p}$

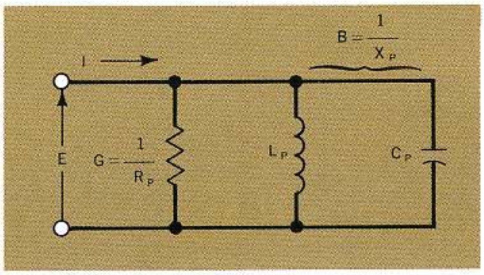
$$\text{Admittance} = Y = 1/E = 1/Z = G \pm jB = |Y| \angle -\Theta$$

where + indicates capacitive susceptance
- indicates inductive susceptance

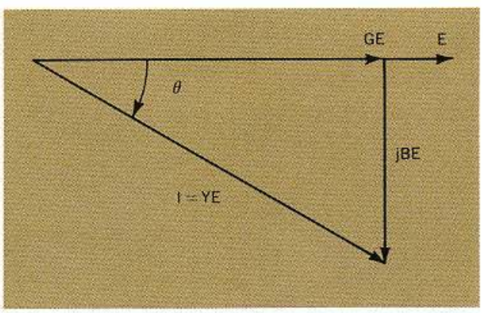
$$\text{Admittance magnitude} = |Y| = \left(G^2 + B^2\right)^{1/2}$$

$$\text{Admittance magnitude} = -\theta = \tan^{-1}(B/G) = \cos^{-1}(G/|Y|)$$
$$= -\tan^{-1}(R_p/X_p)$$

The resulting vector diagram using the admittance parameter in the parallel equivalent circuit is shown in Figure 36B.



Parallel equivalent circuit



Vector diagram for parallel equivalent circuit

Fig. 36.

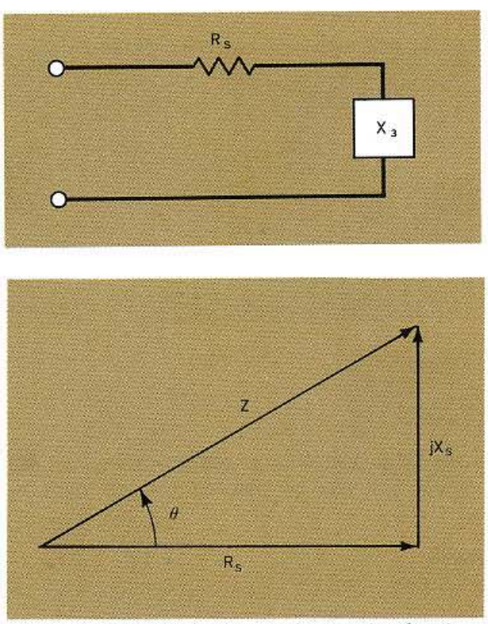


Fig. 37. Resolving the impedance triangle of a equivalent series circuit.

SERIES EQUIVALENT

The Vector Impedance Meters read out the impedance at the terminals of the unknown. The component values of the equivalent series circuit can be determined by resolving the impedance triangle into the rectangular coordinates.

$$R_s = |Z| \cos\theta$$
$$X_s = |Z| \sin\theta$$

PARALLEL EQUIVALENT

Since admittance is the reciprocal of impedance, it is readily obtained by taking the reciprocal of the readings on the |Z| meter and taking the negative of the phase reading. The components of the parallel equivalent circuit can be determined by resolving the admittance triangle.

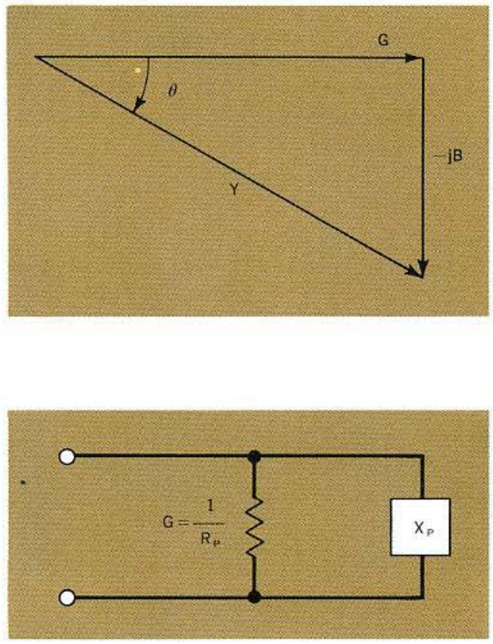


Fig. 38. Resolving the admittance triangle of a parallel equivalent circuit.

$$Y = \frac{1}{|Z|} \angle -\theta = |Y| \angle -\theta = \frac{1}{|Z| \angle \theta}$$
$$G = |Y| \cos\theta = 1/R_p$$
$$B = |Y| \sin\theta = 1/X_p$$

CONVERSION FROM SERIES TO PARALLEL EQUIVALENT

It can be seen that measurements of Z, Θ are extremely convenient since they allow relatively simple conversion between the equivalent parallel and series circuits. The component values of the parallel equivalent circuit can also be calculated directly from the series equivalent circuit as shown below.

$$G + jB = \frac{1}{R_s + jX_s}$$

$$\frac{1}{R_s + jX_s} \quad \frac{R_s - jX_s}{R_s - jX_s} = \frac{R_s - jX_s}{R_s^2 + X_s^2}$$

$$G = \frac{R_s}{R_s^2 + X_s^2} = \frac{1}{R_p}$$

$$B = \frac{-X_s}{R_s^2 + X_s^2} = -\frac{1}{X_p}$$

NATURE OF Q

Q has been used as a measure of impedance for many years. One bit of information contained in Q is bandwidth. High Q has always been a way to express narrow bandwidth, or selectivity. Likewise, low Q indicates broad bandwidth. Besides bandwidth, Q has provided a way to find a small resistive impedance in the presence of a large reactive impedance. Thus, real impedance behavior of circuit elements, such as inductors, is determined by Q.

The basic definition of Q is the ratio of the energy dissipated to the energy stored per cycle in the system. The constant of proportionality is 2π.

$$Q = 2\pi \frac{\text{E stored}}{\text{E dissipated per cycle}}$$

Since the energy dissipated per cycle is a function of frequency, Q becomes a function of frequency. In the following sections, both parallel and series resonant circuits will be examined in connection with Q.

Resonance can be defined by one of three criteria; the frequency of zero phase angle, the frequency where the capacitive reactance equals the inductive reactance, or the frequency of maximum impedance (parallel resonance) or minimum impedance (series resonance).

Resonance equations:

$$\theta = 0^o$$
$$X_c = X_L$$
$$Z = Z \text{ maximum (parallel)}$$
$$Z = Z \text{ minimum (series)}$$

The above equations are not necessarily true at the same frequency. However, if Q is greater than 10, the frequency will be approximately the same.

Derivation of $Q = \omega L/R_s$, $1/\omega CR_s$ for RLC Series Resonant Circuits:

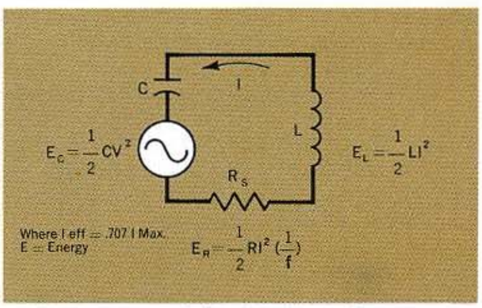


Fig. 39. Energy relationships in an elementary ac series circuit.

Working from the basic definition of Q,

$$Q = 2\pi \frac{\text{total energy stored}}{\text{total energy dissipated per cycle}}$$

The special series RLC resonant circuit formula $\omega L/R_s$ will be derived in the following discussion. The total energy stored in a series RLC resonant circuit oscillates between the inductor and capacitor. Although oscillating, the total stored energy is constant at a given frequency. Assuming, at a given position of the cycle, all the energy is stored in the inductor, the expression of total stored energy becomes:

$$E_{stored} = 1/2\, L\, I^2$$

The energy dissipated by the series resistance is:

$$E_{dissipated} = 1/2\, R_s\, I^2$$

The energy dissipated per cycle is:

$$E_{dissipated/cycle} = 1/2\, R_s\, I^2\, (1/f)$$

The ratio of energy stored to energy dissipated per cycle equals $Q/2\pi$.

$$\frac{Q}{2\pi} = \frac{E_{stored}}{E_{dissipated/cycle}} = \frac{1/2\, L\, I^2}{1/2\, R_s\, I^2\, (1/f)}$$

Therefore:

$$Q = \frac{2\pi fL}{R_s} = \frac{\omega L}{R_s}$$

Since: $L_s = \frac{1}{\omega^2 C}$

$$Q = \frac{1}{\omega CR_s}$$

Deriation of $Q = R_p/\omega L_p = CR_p$ for RLC Parallel Resonant Circuits:

The parallel RLC resonance circuit is shown in Figure 40A. An equivalent of this circuit is shown in Figure 40B. It is for this equivalent circuit that $Q = R_p/\omega L$ applies.

The impedance seen by the current, I, in circuit Figure 40A is:

$$Z = \frac{\left(-j\, \frac{1}{\omega C}\right)(j\,\omega L + R_s)}{\left(-j\, \frac{1}{\omega C}\right) + (j\,\omega L + R_s)}$$

Using the resonance equation:

$$X = \frac{1}{\omega C} = \omega L$$

The impedance becomes:

$$Z = \frac{X^2 - jXR_s}{R_s} = \frac{X^2}{R_s} + (-jX)$$

The impedance magnitude is:

$$|Z| = \left[\left(\frac{X^2}{R_s}\right)^2 + X^2\right]^{1/2} = X\left[\frac{X^2}{{R_s}^2} + 1\right]^{1/2}$$

$$= \omega L\ (Q^2 + 1)^{1/2} = Q\,\omega\,L \text{ if } Q > 10$$

Therefore, $|Z| = Q\omega L$ for large Q. From Ohm's Law, the current, I, through the circuit is:

$$I = \frac{V}{Q\,\omega\,L}$$

Referring to the equivalent parallel circuit, Figure 40B, the current flows entirely through R_p since a perfect parallel tank circuit has an infinite impedance.

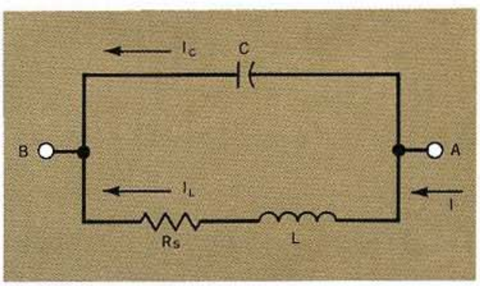
$$|Z| = Q\,\omega\,L = \frac{\omega^2 L^2}{R_s} \longrightarrow \infty \text{ if } R_s \longrightarrow 0$$

It follows that the current through the equivalent tank circuit is:

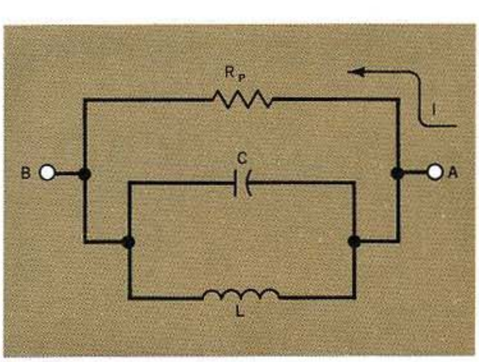
$$I = V/R_p$$

Equating the currents:

$$\frac{V}{Q\,\omega\,L} = \frac{V}{R_p} \quad \text{or} \quad Q\,\omega\,L = R_p$$



(A)



(B)

Fig. 40. (A) Tank circuit configuration.
(B) Parallel equivalent across terminals A B.

Rewriting:

$$Q = \frac{R_p}{\omega L} = \omega C R_p, \text{ since } \frac{1}{\omega C} = \omega L$$

Summarizing from the above discussion,

$$Q = \frac{\omega L}{R_s} = \frac{1}{\omega C R_s} = \frac{R_p}{\omega L} = \omega C R_p$$

These relationships are true for resonance circuits with large Q; i.e., $Q > 10$.

Q AS AN INDICATION OF SELECTIVITY OR BANDWIDTH

By extending the analysis of power relationship in RLC circuits, an expression describing the selectivity or response versus frequency in the vicinity of resonance can be derived. First, two reference points need be established on the resonance curve. The points occur at frequencies at which the power in the circuit is one half the power at resonance. The reactance equals the resistance at these frequencies.

$$Z = \left({R_s}^2 + X^2\right)^{1/2} = \left(2{R_s}^2\right)^{1/2} = 1.414\,R_s$$

$$\text{if } R_s = X$$

The impedance Z consists of equal resistive and reactive components. The resistive component consumes power. Applying the same voltage at the selected frequencies at resonance, will produce a current $I_f = 0.707 I_o$, where I_o is the current at resonance. The power dissipated is then:

$$\omega_f = {I_f}^2 R_s = (.707 I_o)^2 R_s = .5 {I_o}^2 r = 0.5\,\omega_o$$

In other words, it is half the power dissipated at resonance.

The next step is to examine the frequency relationships involved at the point where $X = R_s$. The net reactance changes due to two contributions in the same direction. One, there is a small change in inductive reactance resulting from a change in frequency. Two, there is a small change in capacitive reactance. The net result of these changes is a change in reactance from zero reactance:

$$\Delta X = 2\,(2\pi\,\Delta f L)$$

The change in frequency, Δf, is the difference between f_o and either half power f_1 or f_2. At half power:

$$R_s = 4\pi\,(f_o - f_1)\,L$$
$$R_s = 4\pi\,(f_2 - f_o)\,L$$

Adding the above equation:

$$2R = 4\pi\,(f_2 - f_1)\,L$$

Rewriting and multiplying by f_o:

$$\frac{f_o}{f_2 - f_1} = \frac{2\pi f_o L}{R_s} = \frac{X_L}{R_s} = Q$$

Thus, the above expression for Q is a measure of bandwidth.

Recalling the initial assumption that $X = R$, the phase at f_1 and f_2 will be $+45^o$ and -45^o. These frequency points are now readily determined on the Vector Impedance Meters.

$$\text{at } f_o \ \theta = 0^o$$

$$\text{at } f_1 \ \theta = \pm 45^o$$

$$\text{at } f_2 \ \theta = \pm 45^o$$

TRANSMISSION LINE EQUATIONS

The general formula for a lossless line of unit length, having a characteristic impedance of Z_o and terminated in an impedance Z_L is:

$$Z_i = Z_o \left(\frac{Z_L \cos \beta 1 + jZ_o \sin \beta 1}{Z_o \cos \beta 1 + jZ_L \sin 1\beta} \right) \qquad (1)$$

where the phase constant $\beta = 2\pi / \lambda$, and λ = wavelength. Now if the line is 1/2 wavelength long, $1 = \lambda /4$ and:

$$\beta 1 = \frac{2\pi}{\lambda} \times \frac{\lambda}{4} = \frac{\pi}{2} \text{ radians, or } 90^o$$

Substituting in (1) above:

$$Z_i = Z_o \frac{(+jZ_o)}{(+jZ_L)} = \frac{Z_o^2}{Z_L} \text{ and}$$

$$Z_o = \sqrt{Z_i Z_L} \qquad (2)$$

If the line is 1/8 wavelength long and is short circuited, then $1 = \lambda/8$, $\beta 1 = \pi/4$ radian or 45^o, and $Z_L = 0$. Substituting in (1):

$$Z_i = Z_o \left(\frac{+jZ_o \sin 45^o}{Z \cos 45^o} \right) = +jZ_o = X \qquad (3)$$

In a similar manner it can be shown that the input impedance of a 1/8 wavelength line that is open circuited is:

$$Z_i = jZ_o \qquad (4)$$

For the purpose of deriving a means of measuring the attenuation of a transmission line, the general expression for a line with loss is given below. The impedance, $Z_i{}^1$, looking into a line with loss having a characteristic impedance of Z_o and terminated in an impedance Z_R can be expressed as:

$$Z_i{}^1 = Z_o \left(\frac{Z_R + Z_o \tanh \gamma 1}{Z_o + Z_R \tanh \gamma 1} \right) \qquad (5)$$

where, $1 = \alpha 1 + j \beta 1$, and $\beta = 2\pi / \lambda$.

In the case of a half-wavelength line:

$$1 = \lambda/2$$
$$\beta 1 = 2\pi/\lambda \times \lambda/2 = \pi \quad \text{and}$$
$$\gamma 1 = \alpha 1 + j\pi \quad . \text{ Also,}$$
$$\tanh \gamma 1 = \tanh(\alpha 1 \, j \, \pi) - \tanh \alpha 1.$$

If $\alpha 1$ is small, then $\tanh \alpha 1 = \alpha 1$ and

$$\tanh \gamma 1 = \alpha 1.$$

Substituting in (5) above:

$$Z_i{}^1 = Z_o \left(\frac{Z_R + Z_o \ \alpha 1}{Z_o + Z_R \ \alpha 1} \right)$$

Dividing numerator and demoninator of the fraction on the right by Z_R, we obtain:

$$Z_i{}^1 = Z_o \left[\frac{1 + \frac{Z_o \alpha 1}{Z_R}}{\frac{Z_o}{Z_R} + \alpha 1} \right] \qquad (6)$$

If the half-wavelength cable is open-circuited; i.e., $Z_R = \infty$, (5) will reduce to:

$$Z_i{}^1 = (Z_o) \frac{(1)}{\alpha 1} = \frac{Z_o}{\alpha 1} \text{ and}$$

$\alpha 1 = Z_o/Z_i{}^1$ nepers. Then,

$\alpha 1 = Z_o/Z_i{}^1 \times 8.69$ dB, where $Z_i{}^1$ is resistive and is measured directly.

The calculator may also be used to determine scale factor when component measurements are being made with the Vector Impedance Meters. That is to say, the calculator serves as a scale factor "nanograph" when the Vector Impedance Meters are set to a frequency at which reactance is direct reading (1.592×10^n as discussed on Page 5). For instance, if the 4800A frequency is set to 1.59 kHz, the X1 range is direct reading in microhenries from 100 μH to 1,000 μH. This may be determined from the calculator by setting the frequency 1.59 kHz opposite the arrow. The direct reading inductance range is then read opposite the appropriate impedance. In the example above, 100 μH is read opposite 1Ω and 1,000 μH is read opposite 10Ω.

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